Department of Computer Engineering,

City College of New York

CSC 342 – Computer Organization [CSC 342_Spring_2023]

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Take Home Final Test:

Optimization of dot product computation of two vectors using vector instructions

On Windows intel x64 processer, and Linux Ubuntu

Contents

Objective

The purpose of this final take-home assignment is to learn to optimize compiler-generated code for computing dot products using vector instructions. First, I needed to determine my processor's CPU ID. The CPU provides the instructions and processing power necessary for the computer to function. Generally, the higher the clock speed per core, the better the CPU. We will then generate C++ codes for the dot product, disabling and enabling automatic parallelization and automatic vectorization in separate instances. We will also inspect the compiler-generated assembly code to see if the compiler has vectorized the code for very large vector sizes, and then optimize it accordingly. Finally, based on the optimized code, we will generate assembly code and manually optimize our assembly code and we will use DPPS.

For each step, we will measure execution time and plot time versus vector size. Moreover, all the tasks will be generated one time on Windows, Intel(R) Core (TM) i7, using Visual Studio, and one time on Linux, Ubuntu using gcc.

Task 1 - CPU ID

Windows – Intel x64

To find my CPU ID, I can use a command prompt like *Figure 1*. However, using the command prompt does not provide detailed information about specific vector instruction sets. For finding vector instruction sets we can use CPU Z.

The below Figure shows the CPU ID using the command prompt on Windows. For finding the CPU ID from the command prompt, we can run the commands line below.

```
wmic                    // Windows Management Instrumentation Command-line which
                        allows to access management information.

cpu get                 // show us information about the CPU (processor) in the
                        system.

cpu get processorId     // show us the Processor ID of the CPU.
```

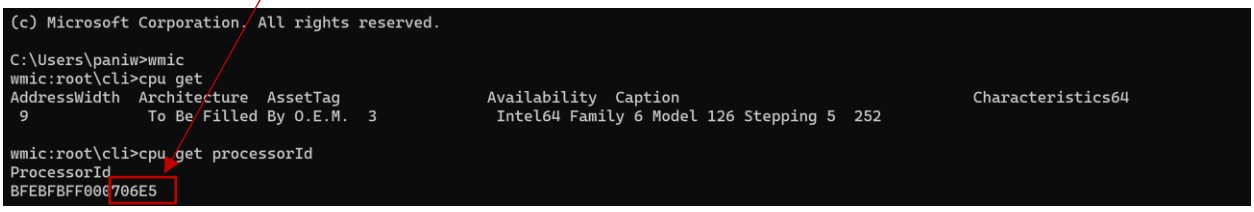


Figure 1 - CPU ID using command prompt

For finding detailed information about specific vector instruction sets that my CPU support, we can use CPU Z.

From CPU Z, we can find our processor name, vector sets that are available, core speed, etc.

Based on the vectors instruction we have:

MMX, SSE, SSE2, SSE3, SSSE3, SSE4.1, and SSE4.2 which are for streaming SIMD extensions.

EM64T or Intel 64 or AMD64 is for Extended Memory 64 Technology.

VT-x or virtualization technology is a hardware virtualization technology developed by Intel.

AVX, and AVX2 are for advanced vector extensions.

AVX-512 is for advanced vector extensions 512-bit.

FMA3 is for fused multiply-add 3.

SHA or secure hash algorithm is a family of cryptographic hash functions used for data integrity and authentication.

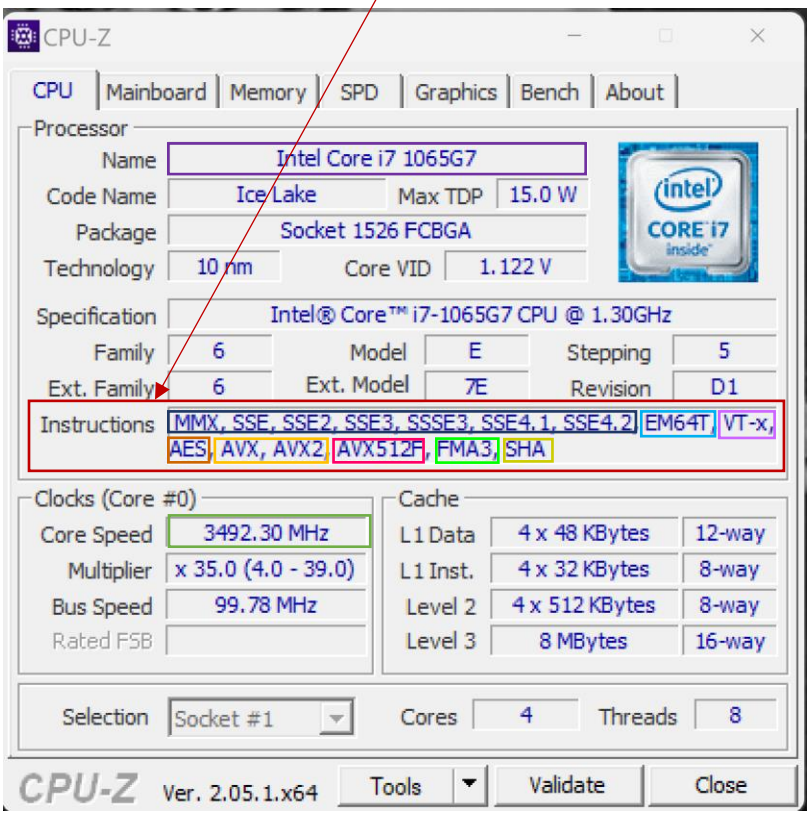


Figure 2 - CPU ID using CPU Z on Windows

Linux - Ubuntu

To find the CPU ID on Linux, we can run the command line on the Linux terminal.

To find the CPU Model we can run below command line:

```
lscpu | grep "Model name"        // CPU architecture information | global regular
                                 expression print
```

```
paniz@paniz-VirtualBox:~/Desktop$ lscpu | grep "Model name"
Model name:                      Intel(R) Core(TM) i7-1065G7 CPU @ 1.30GHz
paniz@paniz-VirtualBox:~/Desktop$
```

Figure 3 - CPU ID on Linux

To find the CPU ID with specifications for vector processing capabilities, we can run the below command:

```
Lscpu                            // CPU architecture information
```

In *Figure 4*, from Flags we can find the vector specification.

```
paniz@paniz-VirtualBox:~/Desktop$ lscpu
Architecture:            x86_64
  CPU op-mode(s):        32-bit, 64-bit
  Address sizes:         39 bits physical, 48 bits virtual
  Byte Order:            Little Endian
CPU(s):                  4
  On-line CPU(s) list:   0-3
Vendor ID:               GenuineIntel
  Model name:            Intel(R) Core(TM) i7-1065G7 CPU @ 1.30GHz
    CPU family:          6
    Model:               126
    Thread(s) per core:  1
    Core(s) per socket:  4
    Socket(s):           1
    Stepping:            5
    BogoMIPS:            2995.20
    Flags:               fpu vme de pse tsc msr pae mce cx8 apic sep mtrr pge mc
                         a cmov pat pse36 clflush mmx fxsr sse sse2 ht syscall n
                         x rdtscp lm constant_tsc rep_good nopl xtopology nonsto
                         p_tsc cpuid tsc_known_freq pni pclmulqdq ssse3 cx16 pci
                         d sse4_1 sse4_2 x2apic movbe popcnt aes xsave avx rdran
                         d hypervisor lahf_lm abm 3dnowprefetch invpcid_single f
                         sgsbase bmi1 avx2 bmi2 invpcid rdseed clflushopt md_cle
                         ar flush_l1d arch_capabilities
Virtualization features:
  Hypervisor vendor:     KVM
  Virtualization type:   full
Caches (sum of all):
  L1d:                   192 KiB (4 instances)
  L1i:                   128 KiB (4 instances)
  L2:                    2 MiB (4 instances)
  L3:                    32 MiB (4 instances)
NUMA:
  NUMA node(s):          1
```

Figure 4 - CPU ID for vector specification on Linux

```
  NUMA node0 CPU(s):     0-3
Vulnerabilities:
  Itlb multihit:         KVM: Mitigation: VMX unsupported
  L1tf:                  Not affected
  Mds:                   Not affected
  Meltdown:              Not affected
  Mmio stale data:       Vulnerable: Clear CPU buffers attempted, no microcode;
                         SMT Host state unknown
  Retbleed:              Vulnerable
  Spec store bypass:     Vulnerable
  Spectre v1:            Mitigation; usercopy/swapgs barriers and __user pointer
                          sanitization
  Spectre v2:            Mitigation; Retpolines, STIBP disabled, RSB filling, PB
                         RSB-eIBRS Not affected
  Srbds:                 Unknown: Dependent on hypervisor status
  Tsx async abort:       Not affected
paniz@paniz-VirtualBox:~/Desktop$
```

Figure 5 – Rest of the CPU ID for vector specification on Linux

As you see we have similar vector processing capabilities since Ubuntu is installed on a virtual machine on my Windows device with the same hardware, including the CPU. Hence, CPU remains the same for both the host operating system, Windows, and the guest operating system, Ubuntu.

Task 2 - Compute dot product Using C++ (Non-Optimized)

Windows – Intel x64

Based on the requirement, first we need to disable automatic parallelization and automatic vectorization. To disable automatic parallelization and automatic vectorization, we need to do the project properties. In order to get to the project properties, we need to right-click on our project name.

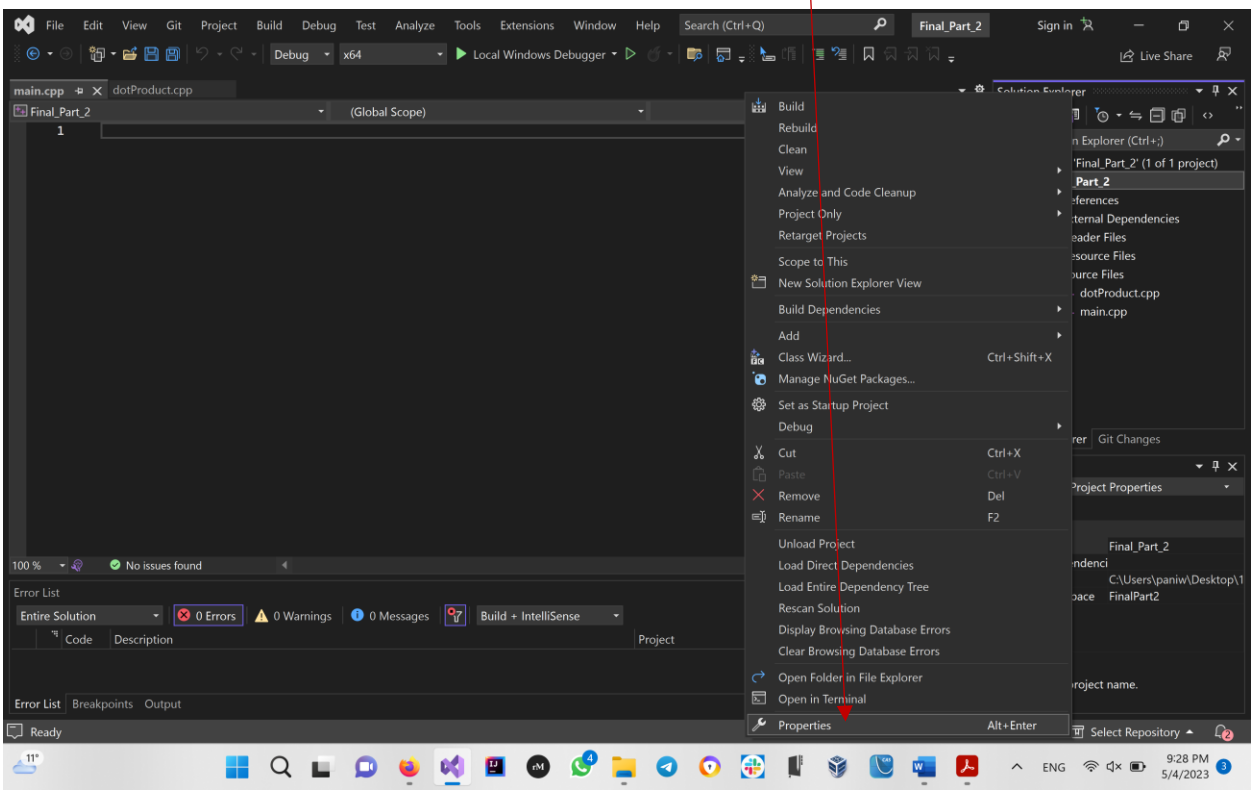


Figure 6 - Project Properties on VS

Once we are in project properties, we can use the steps below to disable Parallel Code Generation and Enhanced Instruction Set.

Project Property, C/C++, Code Generation, and enable Parallel Code Generation by using *No (/Qpar-)* and enable Enhanced Instruction Set by using *No Enhanced Instructions (/arch:IA32)* and then press apply.

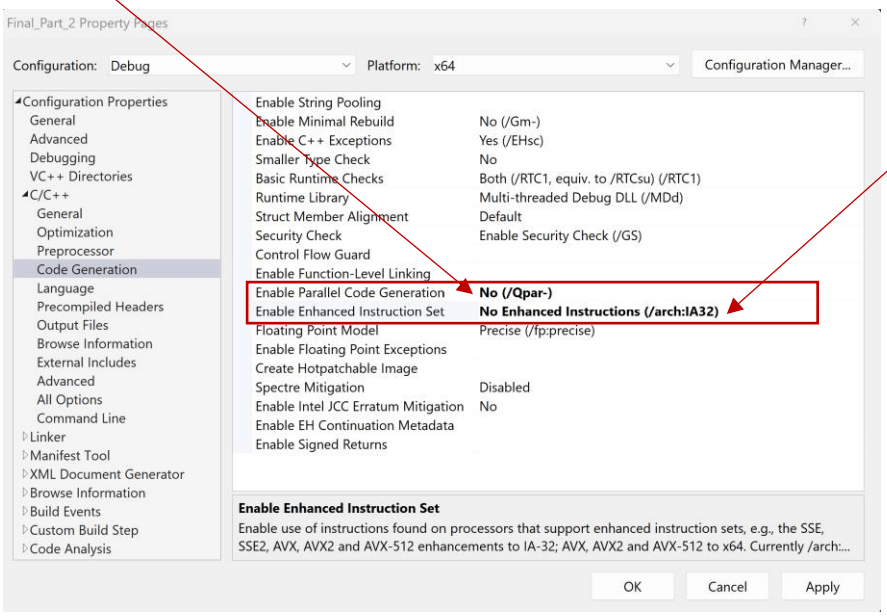


Figure 7 - Enable Parallel Code Generation and Enhanced Instruction Set on VS

We need to also make sure that optimization is not on. We can use the steps below to make sure optimization is unable.

Project Property, C/C++, Optimization, Disable (/Od)

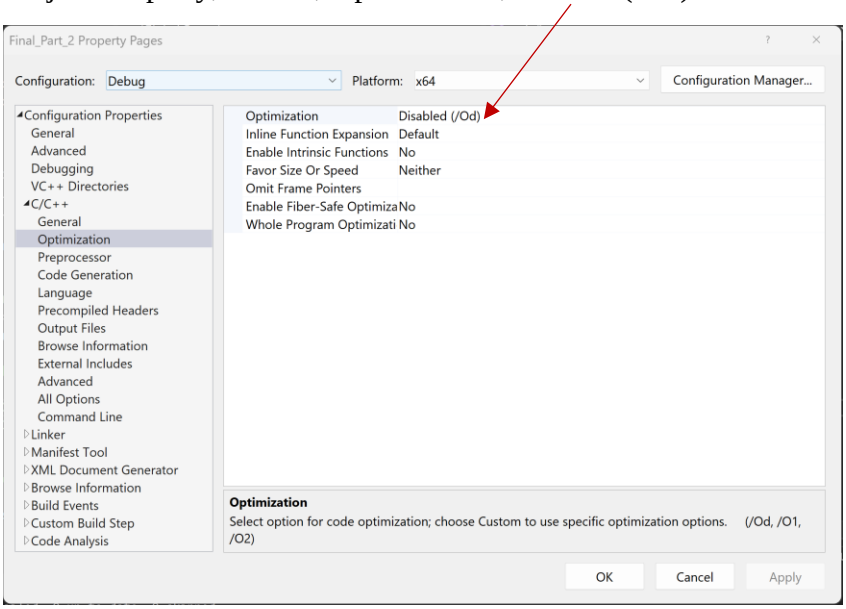


Figure 8 – Disable Optimization on VS

We will have two code files; for instance, we will have a source file - dotProduct.cpp, and a main file - main.cpp. The dotProduct.cpp contains the definition of the dotProduct function which means it is the implementation calculation. The main.cpp contains the vector size and defines a vector of powers of 2 size, and printouts value.

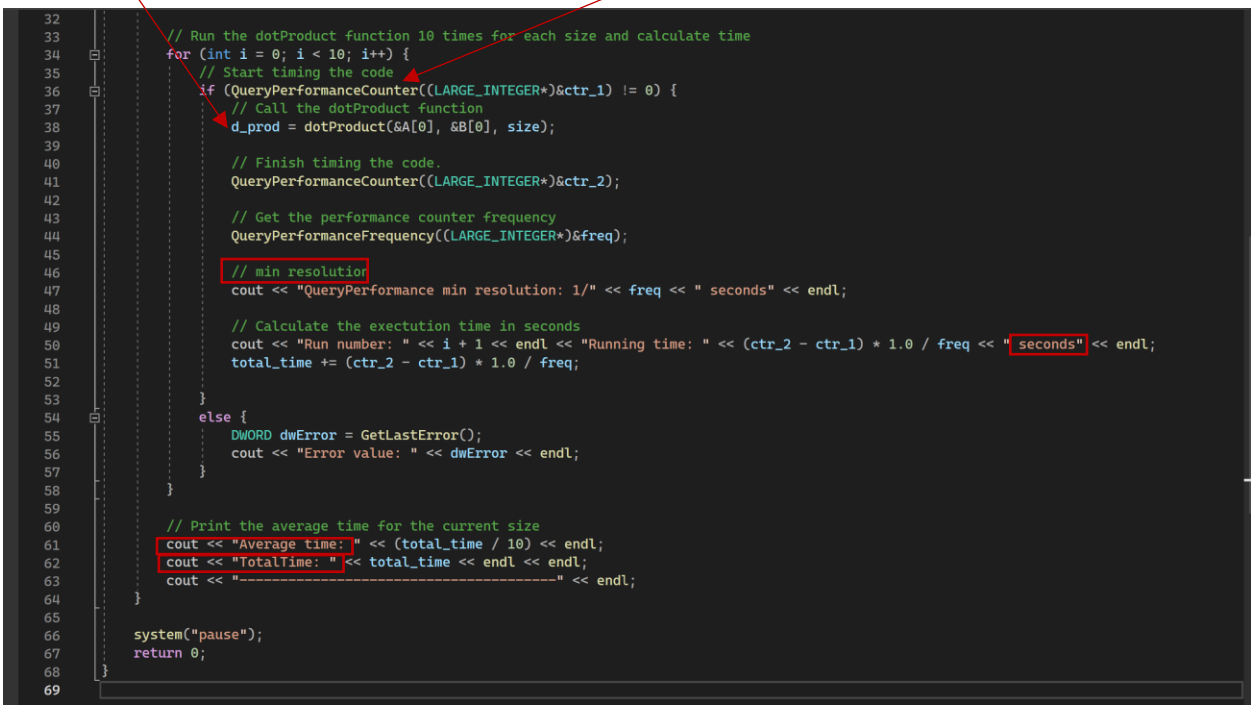
Below on *Figure 9*, you can see the screenshot from my Visual Studio for our main.cpp function. Since we want to use vector, we need to include `<vector>` and `<algorithm>` library, and for QueryPerFormanceCounter we need to include `<windows.h>` library. Next, we will have our array which is set to the largest vector size which is 2^16 for this assignment, and initial our arrays A and B. On line 12, we have a definition of dotProduct, and starting line 14 we will start the main function.

In our main function we declare counter variables, dot product result, and total time and initial all of them to 0. Next, we are initiating the value of our two arrays which are A and B.
We will also define our array size which is from 2^4 to 2^16 based on the requirements and print the array size.

```
1  #include <iostream>
2  #include <vector>       // Library for Vector
3  #include <windows.h>    // Library for QueryPerformanceCounter
4  #include <algorithm>    // std::vector
5
6  using namespace std;
7
8  const int max_arr_size = 65536; // Set the largest vector size to 2^16
9  vector<float> A(max_arr_size); // Vector A
10 vector<float> B(max_arr_size); // Vector B
11
12 float dotProduct(float* arr_1, float* arr_2, const int size);
13
14 int main() {
15     _int64 ctr_1 = 0, ctr_2 = 0, freq = 0;
16     int acc = 0, n = 0, d_prod = 0;
17     double total_time = 0;
18
19     // Initialize the values of A and B
20     for (int n = 0; n < max_arr_size; n++) {
21         A[n] = n / 2.0;
22         B[n] = n / 3.0;
23     }
24
25     // Define the vector of sizes as powers of 2
26     //                      2^4                                                    2^16
27     vector<size_t> sizes = { 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384, 32768, 65536 };
28
29     // print array size
30     for (size_t size : sizes) {
31         cout << "Vector size: " << size << endl;
32
```

Figure 9 - C++ on VS

We will run dotProduct 10 times and for each size. We will use Query to calculate the min resolution, execution time, average time, and total time in seconds and print the values. We also call the dotProduct function that we created in our dotProduct.cpp.



```
32
33          // Run the dotProduct function 10 times for each size and calculate time
34          for (int i = 0; i < 10; i++) {
35              // Start timing the code
36              if (QueryPerformanceCounter((LARGE_INTEGER*)&ctr_1) != 0) {
37                  // Call the dotProduct function
38                  d_prod = dotProduct(&A[0], &B[0], size);
39
40                  // Finish timing the code.
41                  QueryPerformanceCounter((LARGE_INTEGER*)&ctr_2);
42
43                  // Get the performance counter frequency
44                  QueryPerformanceFrequency((LARGE_INTEGER*)&freq);
45
46                  // min resolution
47                  cout << "QueryPerformance min resolution: 1/" << freq << " seconds" << endl;
48
49                  // Calculate the exectution time in seconds
50                  cout << "Run number: " << i + 1 << endl << "Running time: " << (ctr_2 - ctr_1) * 1.0 / freq << " seconds" << endl;
51                  total_time += (ctr_2 - ctr_1) * 1.0 / freq;
52
53              }
54              else {
55                  DWORD dwError = GetLastError();
56                  cout << "Error value: " << dwError << endl;
57              }
58          }
59
60          // Print the average time for the current size
61          cout << "Average time: " << (total_time / 10) << endl;
62          cout << "TotalTime: " << total_time << endl << endl;
63          cout << "---------------------------------------" << endl;
64      }
65
66      system("pause");
67      return 0;
68  }
69
```

Figure 10 - C++ on VS

Run the Code

After we run the code, we will get the below results. *Figure 11* states the result for vector size 2^4 or 16. We can see that the dotProduct ran 10 times and for each time we can see the running time. To make it easier to follow the figures, I added boxes to *Figure 11* to improve clarity and help convey the idea behind each figure. If you look at the Figures, you can see the min resolution stays the same. The reason that we get the same result for the min resolution every time is that the performance counter frequency `freq` is a fixed value for my system. For instance, it is determined by the hardware.

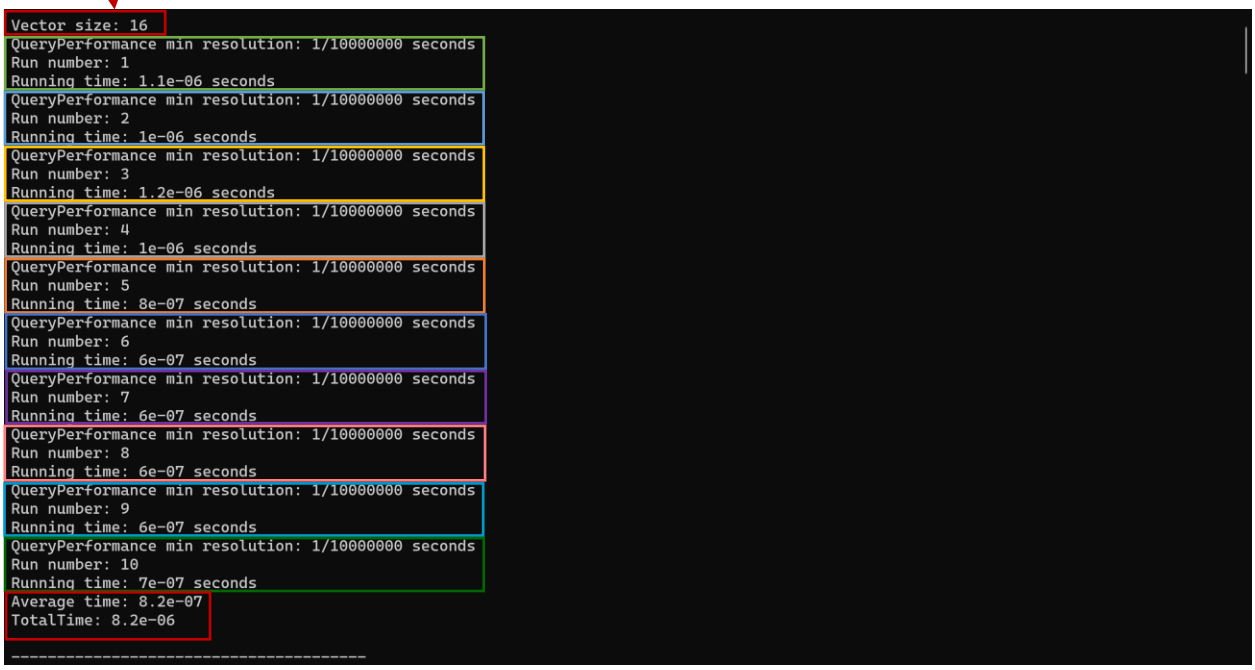


Figure 11 – dot Product for 2^4 without /Qpar and /arch

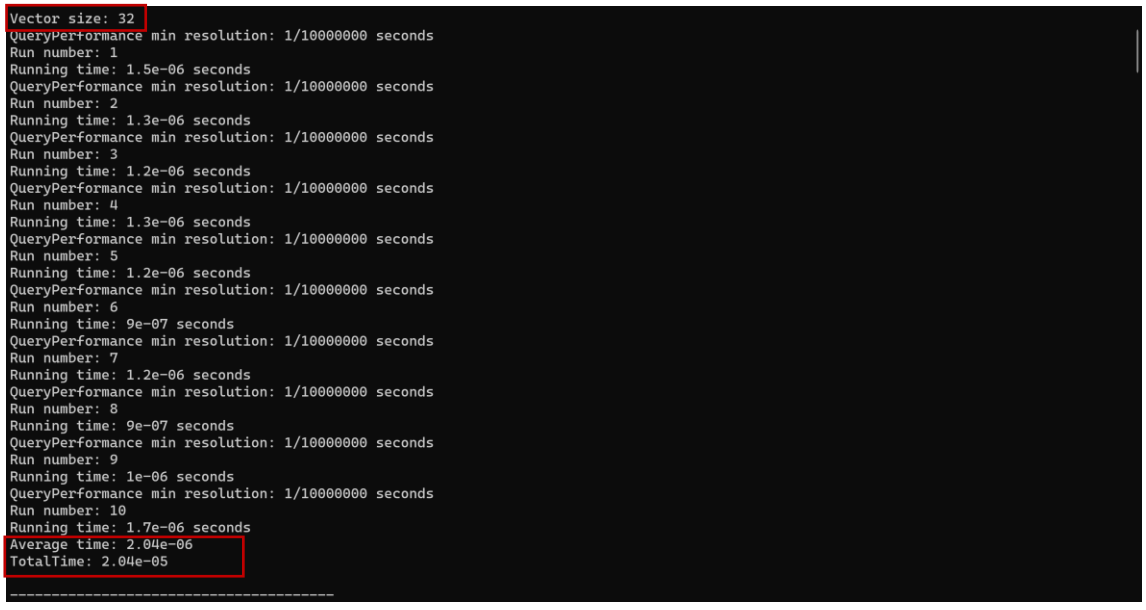


Figure 12 - dot Product for 2^5 without /Qpar and /arch

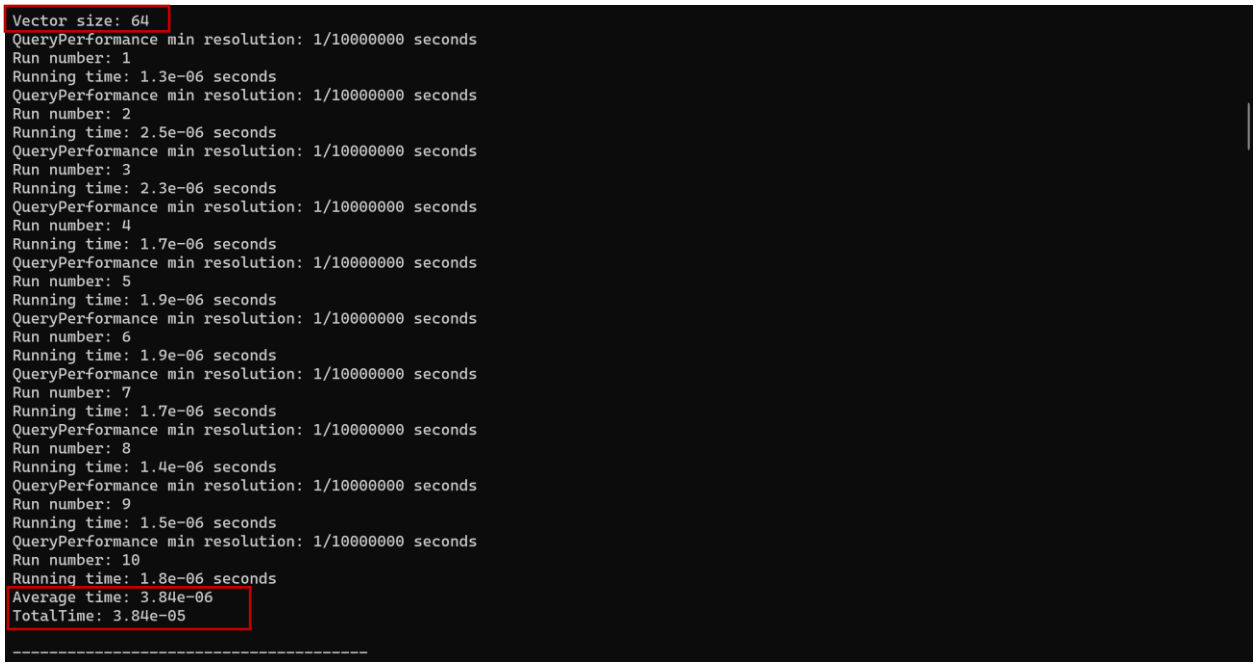


Figure 13 - dot Product for 2^6 without /Qpar and /arch

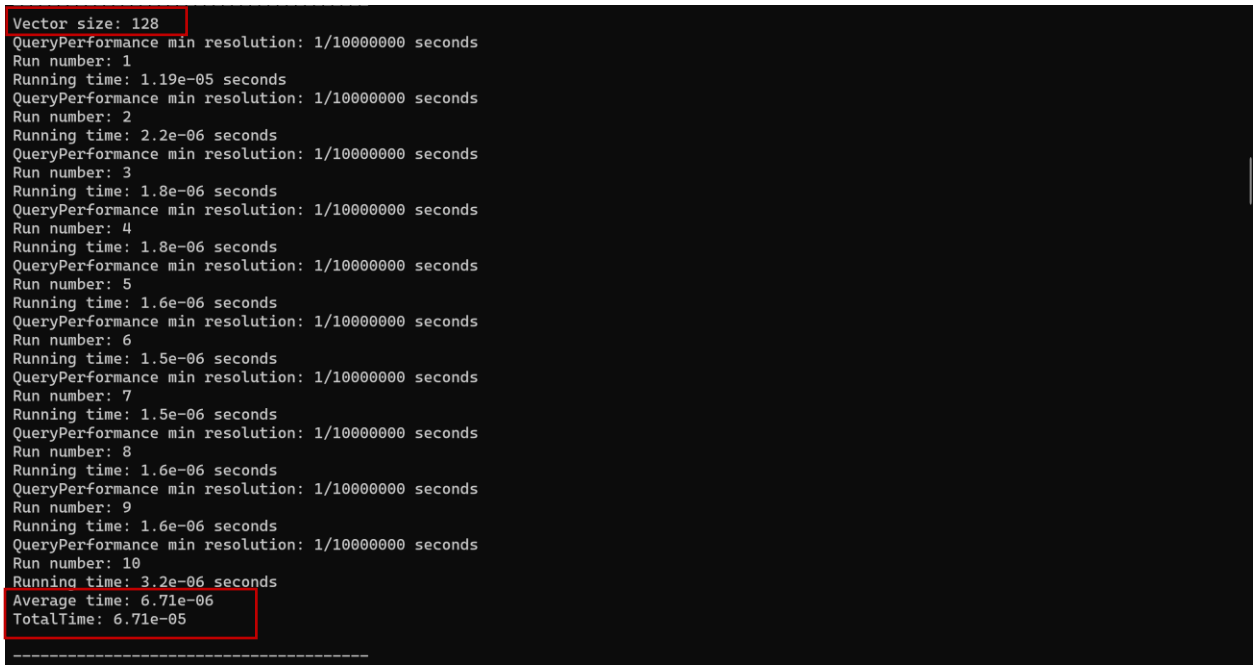


Figure 14 - dot Product for 2^7 without /Qpar and /arch

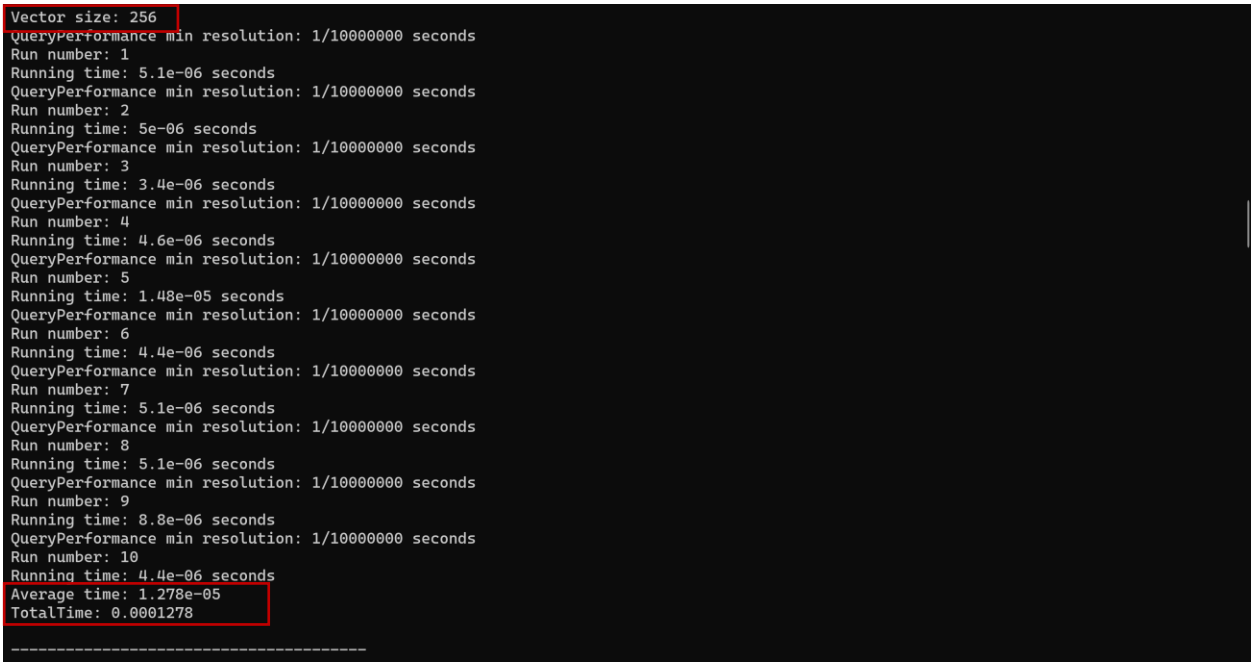


Figure 15 - dot Product for 2^8 without /Qpar and /arch

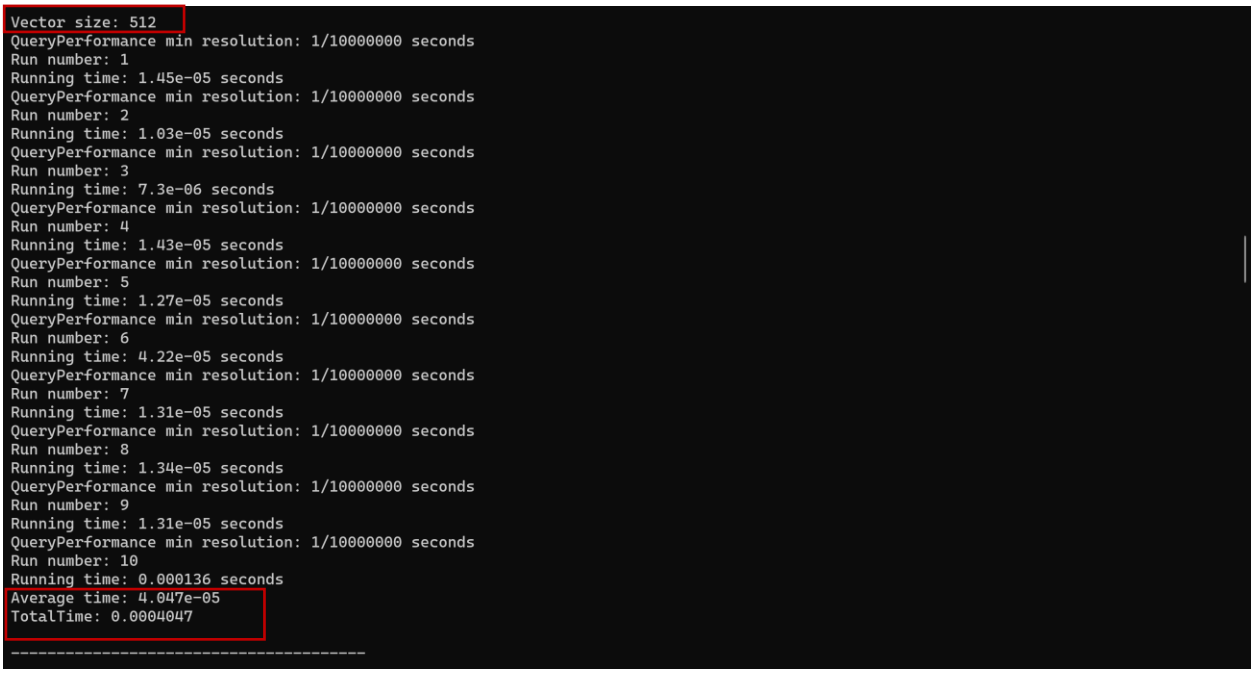


Figure 16 - dot Product for 2^9 without /Qpar and /arch

Figure 17 - dot Product for 2^10 without /Qpar and /arch

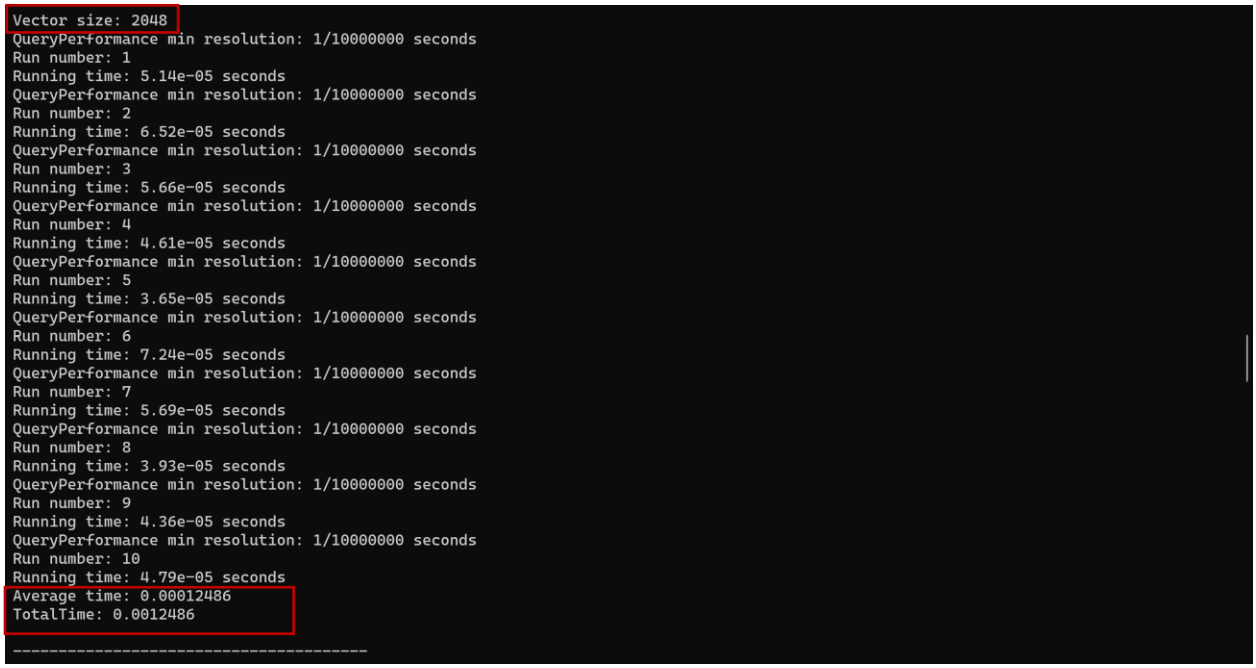


Figure 18 - dot Product for 2^11 without /Qpar and /arch

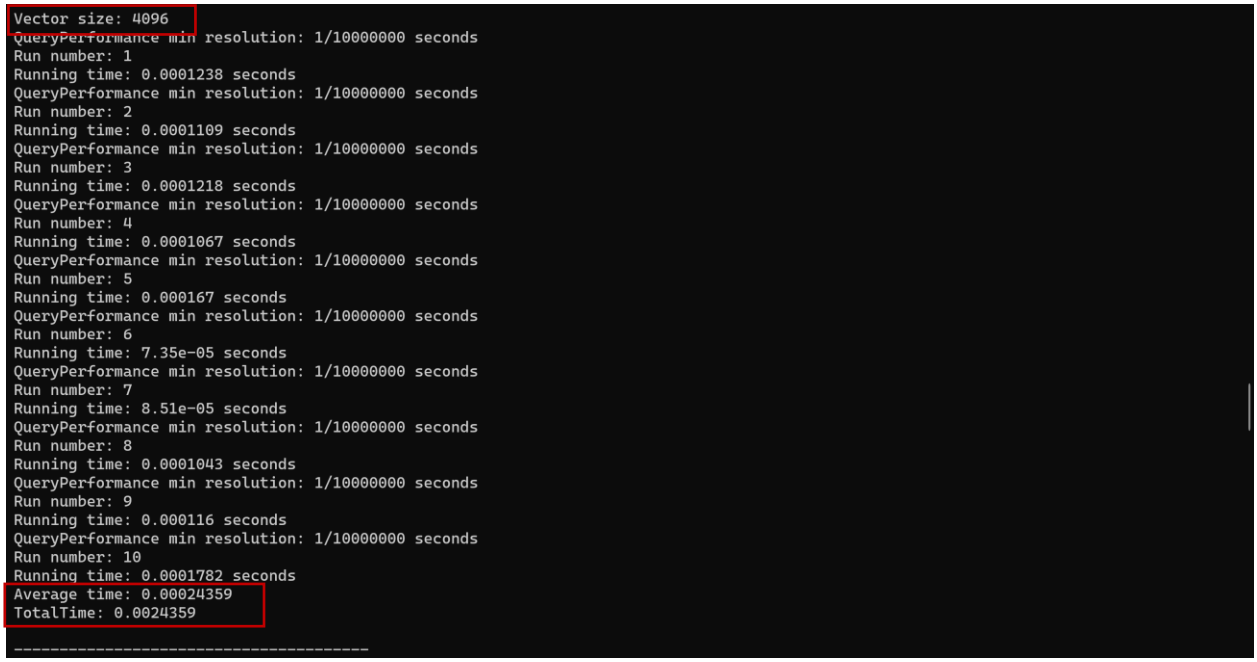


Figure 19 - dot Product for 2^12 without /Qpar and /arch

Figure 20 - dot Product for 2^13 without /Qpar and /arch

Figure 21 - dot Product for 2^14 without /Qpar and /arch

Figure 22 - dot Product for 2^15 without /Qpar and /arch

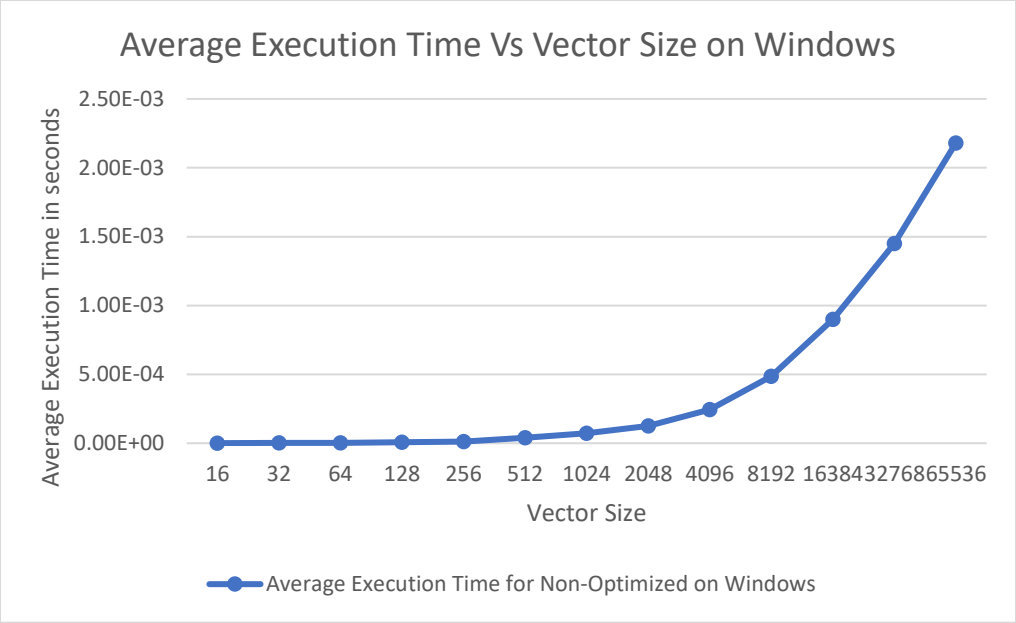
Figure 23 - dot Product for 2^16 without /Qpar and /arch

Graph

Now that we have execution time, we will graph Average Execution time Vs Vector Size for unoptimized code. We ran the code 10 times for each vector size to be able to find the average execution time that is more accurate.

Table 1 - Task 2 - Windows

Vector Size	Average Execution Time in seconds for Non-Optimized on Windows
16	8.20E-07
32	2.04E-06
64	3.84E-06
128	6.71E-06
256	1.28E-05
512	4.05E-05
1024	7.33E-05
2048	1.25E-04
4096	2.44E-04
8192	4.87E-04
16384	9.00E-04
32768	1.45E-03
65536	2.18E-03



Graph 1 – Average Execution Time Vs Vector Size for Non-Optimized on Windows

Linux - Ubuntu

We are using the same C++ codes for the function of dot product. However, some modifications are needed for main.cpp. For instance, the C++ code on Visual Studio uses QueryPerformanceCounter function which is Windows API for measuring time; hence, we need to change it to something that be equivalent of Query but for Linux. We can use the clock_gettime function which is equivalent of QueryPerformanceCounter for Linux.

As you can see in *Figure 24*, first we removed the `include <windows.h>` since now we are using Linux and then used `include <time.h>` which is a time library in Linux that we need to for clock_gettime. The rest of the code stays the same until line 43, which we start to find the execution time.

```
1  #include <iostream>
2  #include <vector>
3  #include <algorithm>
4  #include <time.h>
5
6  using namespace std;
7
8  const int max_arr_size = 65536; // Set the largest vector size to 2^16
9  vector<float> A(max_arr_size); // Vector A
10 vector<float> B(max_arr_size); // Vector B
11
12 // Function to calculate the dot product of two vectors
13 float dotProduct(const std::vector<float>& arr_1, const std::vector<float>& arr_2, const int size);
14
15 int main() {
16     timespec start_time, end_time;
17     double elapsed_time, total_time;
18     int d_prod = 0;
19
20     // Initialize the values of A and B
21     for (int n = 0; n < max_arr_size; n++) {
22         A[n] = n / 2.0;
23         B[n] = n / 3.0;
24     }
25
26     // Define the vector of sizes as powers of 2
27     vector<size_t> sizes = { 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384, 32768, 65536 };
28
29     // Iterate over each vector size
30     for (size_t size : sizes) {
31         cout << "Vector size: " << size << endl;
32         total_time = 0;
```

Figure 24 - C++ on Ubuntu gcc

Starting line 34, we are starting to find the execution time by using clock_gettime. We also need to divide the execution time by 1e9 to get the time in seconds since the `tv_nsec` field stores the time in nanosecond.

```
33
34        // Run the dotProduct function 10 times for each size and calculate time
35        for (int i = 0; i < 10; i++) {
36            // Start timing the code
37            clock_gettime(CLOCK_MONOTONIC, &start_time);
38
39            // Call the dotProduct function
40            d_prod = dotProduct(A, B, size);
41
42            // Finish timing the code
43            clock_gettime(CLOCK_MONOTONIC, &end_time);
44
45            // Calculate the elapsed time in seconds
46            elapsed_time = (end_time.tv_sec - start_time.tv_sec) + (end_time.tv_nsec - start_time.tv_nsec) / 1e9;
47            cout << "Run number: " << i + 1 << endl << "Running time: " << elapsed_time << " seconds" << endl;
48            total_time += elapsed_time;
49        }
50
51        // Print the average time for the current size
52        cout << "Average time: " << (total_time / 10) << endl;
53        cout << "TotalTime: " << total_time << endl << endl;
54        cout << "----------------------------------------" << endl;
55    }
56
57    return 0;
58 }
```

Figure 25 - C++ on Ubuntu gcc

The dotProduct.cpp stays the same as before since it is just definition of dotProduct. We will call the dorProduct.cpp in main.cpp on line 40.

```
1 #include <vector>
2
3 // Definition of the dotProduct function
4 float dotProduct(const std::vector<float>& arr_1, const std::vector<float>& arr_2, const int size) {
5     float result = 0;
6
7     // Iterate through both vectors and calculate the dot product
8     for (int i = 0; i < size; i++) {
9         result += arr_1[i] * arr_2[i];
10    }
11    return result;
12 }
```

Figure 26 - C++ on Ubuntu gcc

Now that we have our code, we need to disable the automatic parallelization and automatic vectorization. For disabling automatic parallelization and automatic vectorization we can use the below command line on Ubuntu gcc.

```
// The -fno-tree-vectorize flag disables automatic vectorization.

// The -fno-tree-loop-distribute-patterns flag disables automatic loop
parallelization.

// We need to link out dotProduct and main as well

// The -O0 will make sure that the code stays unoptimized

g++ -O0 -fno-tree-loop-distribute-patterns -fno-tree-vectorize
Peiravani_Paniz_main.cpp Peiravani_Paniz_dotProduct.cpp -o main
```

```
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ g++ -O0 -fno-tree-loop-distribute-patterns -fno-tree-vectorize
Peiravani_Paniz_main.cpp Peiravani_Paniz_dotProduct.cpp -o main
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ ./main
```

Figure 27 - Compile the C++ code on Linux

Linux gcc has command line flags that we can use for optimizations.

Table 2 - Optimization Flags on Linux gcc

Optimization Flags	Optimizations Level	Optimizations
-o0	O (Default)	None
-o1	1	Basic
-o2	2	Recommended
-o3	3 (Highest)	Not Guaranteed

Run the Code

After we run the code by using `./main` which is our a.out file, we will get the below results. *Figure 28* states the result for vector size 2^4 or 16. We can see that the dotProduct ran 10 times and for each time we can see the running time. To make it easier to follow the figures, I added boxes to *Figure 28* to improve clarity and help convey the idea behind each figure.

Figure 28 - dot Product for 2^4 on Linux

Figure 29 - dot Product for 2^5 on Linux

Figure 30 - dot Product for 2^6 on Linux

Figure 31 - dot Product for 2^7 on Linux

Figure 32 - dot Product for 2^8 on Linux

```
Vector size: 512
Run number: 1
Running time: 4.714e-06 seconds
Run number: 2
Running time: 3.113e-06 seconds
Run number: 3
Running time: 2.767e-06 seconds
Run number: 4
Running time: 1.958e-06 seconds
Run number: 5
Running time: 1.944e-06 seconds
Run number: 6
Running time: 1.943e-06 seconds
Run number: 7
Running time: 1.942e-06 seconds
Run number: 8
Running time: 1.941e-06 seconds
Run number: 9
Running time: 1.938e-06 seconds
Run number: 10
Running time: 1.935e-06 seconds
Average time: 2.4195e-06
TotalTime: 2.4195e-05

-------------------------------------
```

Figure 33 - dot Product for 2^9 on Linux

```
Vector size: 1024
Run number: 1
Running time: 3.921e-06 seconds
Run number: 2
Running time: 3.945e-06 seconds
Run number: 3
Running time: 3.881e-06 seconds
Run number: 4
Running time: 3.872e-06 seconds
Run number: 5
Running time: 3.876e-06 seconds
Run number: 6
Running time: 3.87e-06 seconds
Run number: 7
Running time: 4.049e-06 seconds
Run number: 8
Running time: 3.865e-06 seconds
Run number: 9
Running time: 3.875e-06 seconds
Run number: 10
Running time: 3.874e-06 seconds
Average time: 3.9028e-06
TotalTime: 3.9028e-05

-------------------------------------
```

Figure 34 - dot Product for 2^10 on Linux

```
Vector size: 2048
Run number: 1
Running time: 7.795e-06 seconds
Run number: 2
Running time: 7.722e-06 seconds
Run number: 3
Running time: 7.682e-06 seconds
Run number: 4
Running time: 7.765e-06 seconds
Run number: 5
Running time: 7.882e-06 seconds
Run number: 6
Running time: 7.699e-06 seconds
Run number: 7
Running time: 7.984e-06 seconds
Run number: 8
Running time: 7.707e-06 seconds
Run number: 9
Running time: 7.754e-06 seconds
Run number: 10
Running time: 7.909e-06 seconds
Average time: 7.7899e-06
TotalTime: 7.7899e-05

-------------------------------------
```

Figure 35 - dot Product for 2^11 on Linux

Figure 36 - dot Product for 2^12 on Linux

Figure 37 - dot Product for 2^13 on Linux

Figure 38 - dot Product for 2^14 on Linux

Figure 39 - dot Product for 2^15 on Linux

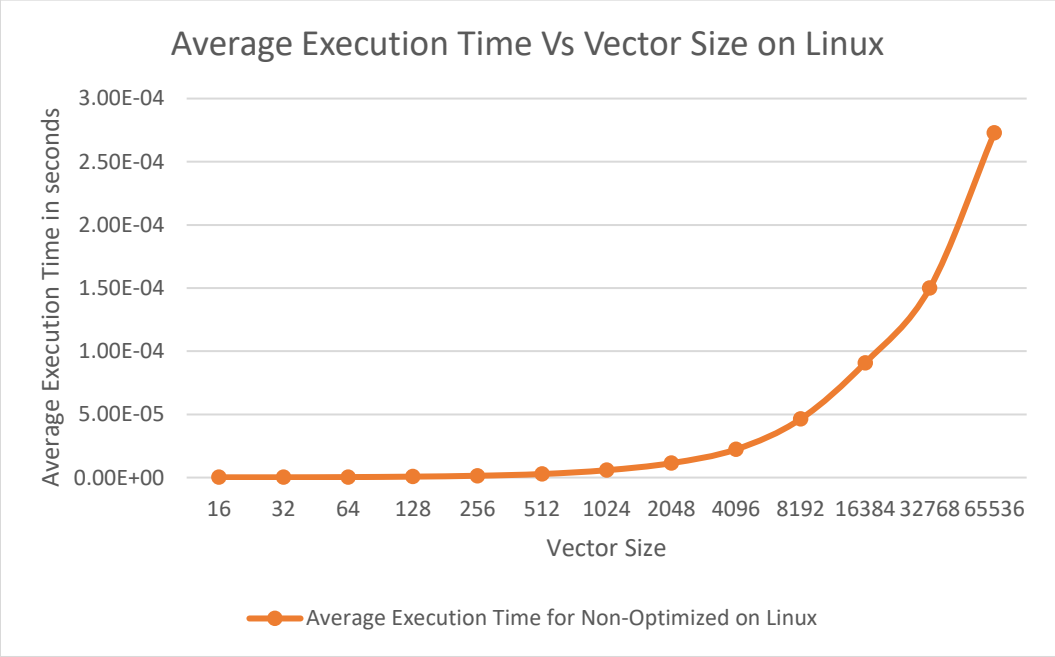
Figure 40 - dot Product for 2^16 on Linux

Graph

Now that we have execution time, we will graph Average Execution time Vs Vector Size for unoptimized code. We ran the code 10 times for each vector size to be able to find the average execution time that is more accurate.

Table 3 - Task 2 - Linux, Ubuntu

Vector Size	Average Execution Time in seconds for Non-Optimized on Linux
16	2.28E-07
32	2.17E-07
64	3.97E-07
128	7.36E-07
256	1.43E-06
512	2.82E-06
1024	5.83E-06
2048	1.14E-05
4096	2.23E-05
8192	4.63E-05
16384	9.07E-05
32768	1.50E-04
65536	2.73E-04



Graph 2 - Average Execution Time Vs Vector Size for Non-Optimized on Linux

Task 3 - Compute dot product Using C++ (Non-Optimized and Optimized)

Windows – Intel x64

Non-Optimized Assembly Code

The Automatic Parallelization, Automatic Vectorization, and optimization from previous task is still disable. To get the non-Optimized assembly code, we can go to the project properties. In order to get to the project properties, we need to right-click on our project name.

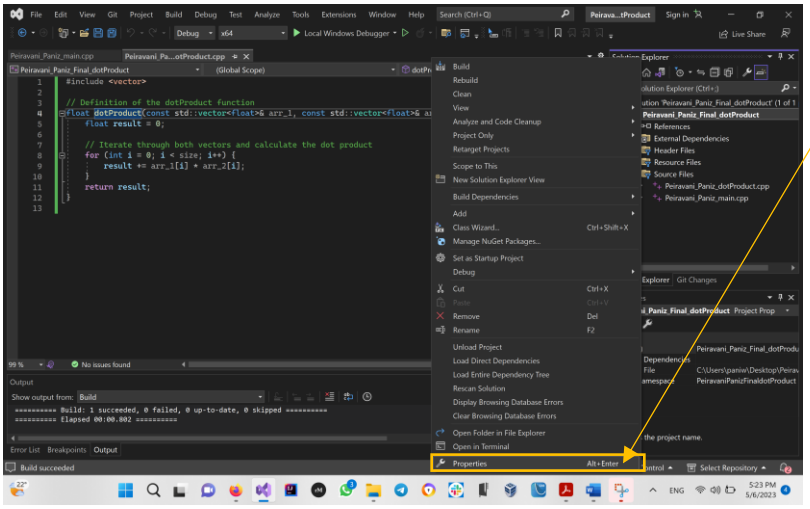


Figure 41 - Project Properties on VS – windows

Once we are in project properties, we can use the steps below to see the assembly code (.asm).

Project Property, C/C++, Output Files, and set the assembly output to *Assembly with Source Code (/FAs)*. The */FAs* will give us the assembly code, *.asm*. If we want *assembly, machine language, and source code* we can use */FAcs* which will give us *.dot*.

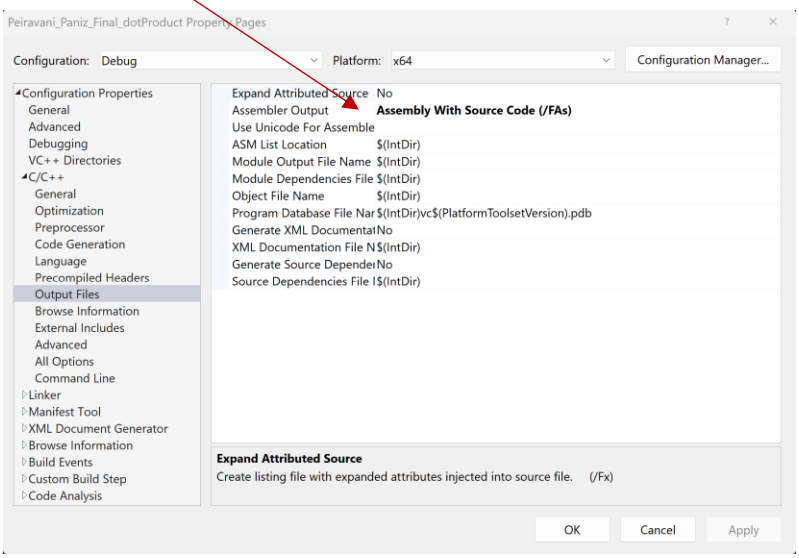


Figure 42 - Assembly Output on windows

Once we build our code, we can go to the project folder and we will see .asm output.

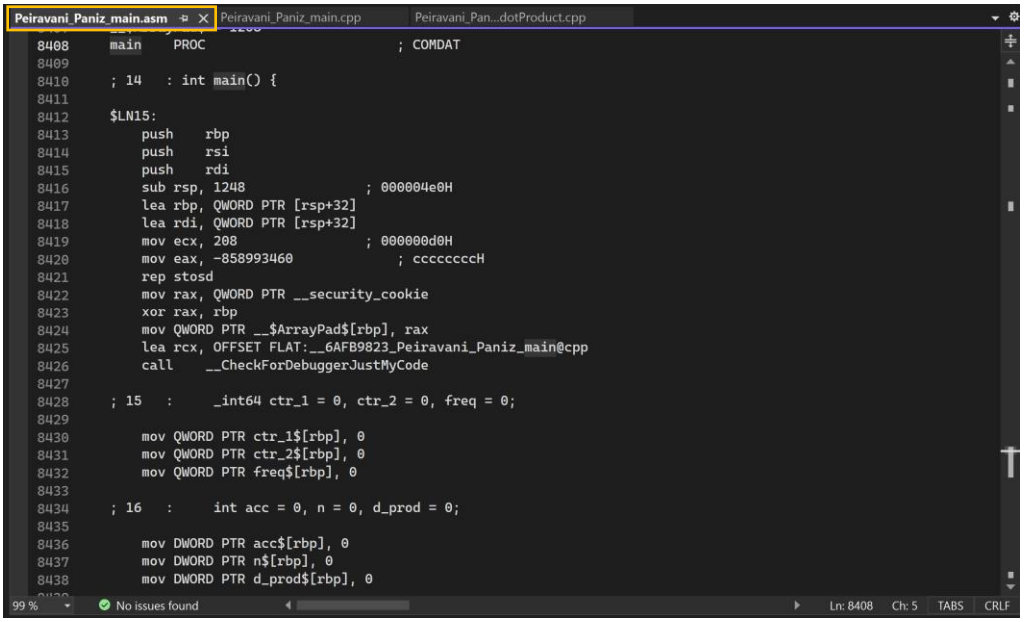


Figure 43 - .asm file for main.cpp - Non-Optimized

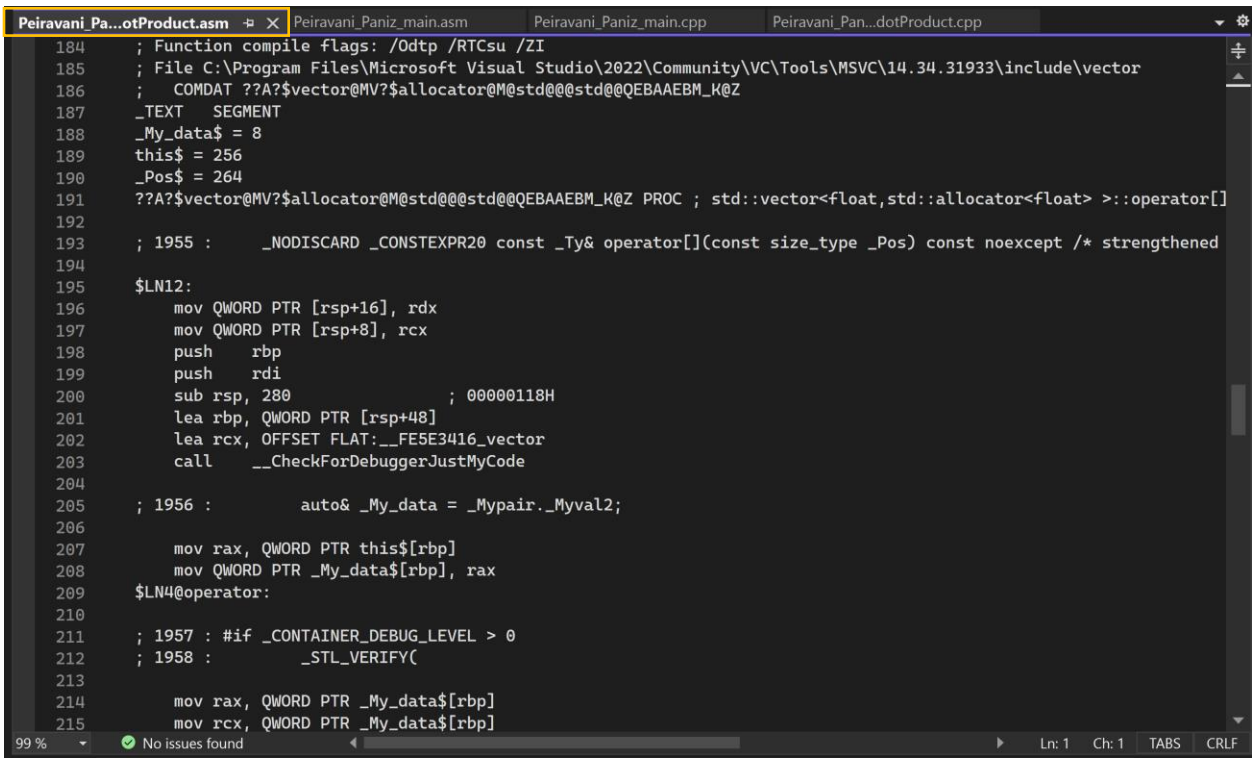


Figure 44 - .asm file for dotProduct.cpp - non-Optimized

It will give us 11170 lines of code for main.cpp and 351 line of code for dotProduct.cpp when our code is not optimized.

```
11161         lea rcx, OFFSET FLAT:__6AFB9823_Peiravani_Paniz_main@cpp
11162         call    __CheckForDebuggerJustMyCode
11163         lea rsp, QWORD PTR [rbp+200]
11164         pop rdi
11165         pop rbp
11166         ret 0
11167     ?__empty_global_delete@@YAXPEAX@Z ENDP          ; __empty_global_delete
11168     _TEXT   ENDS
11169     END
11170
```

Figure 45 - asm file for dotProduct.cpp - non-Optimized for main.cpp

```
346         pop rdi
347         pop rbp
348         ret 0
349     ?dotProduct@@YAMAEBV?$vector@MV?$allocator@M@std@@@std@@@0H@Z ENDP ; dotProduct
350     _TEXT   ENDS
351     END
352
```

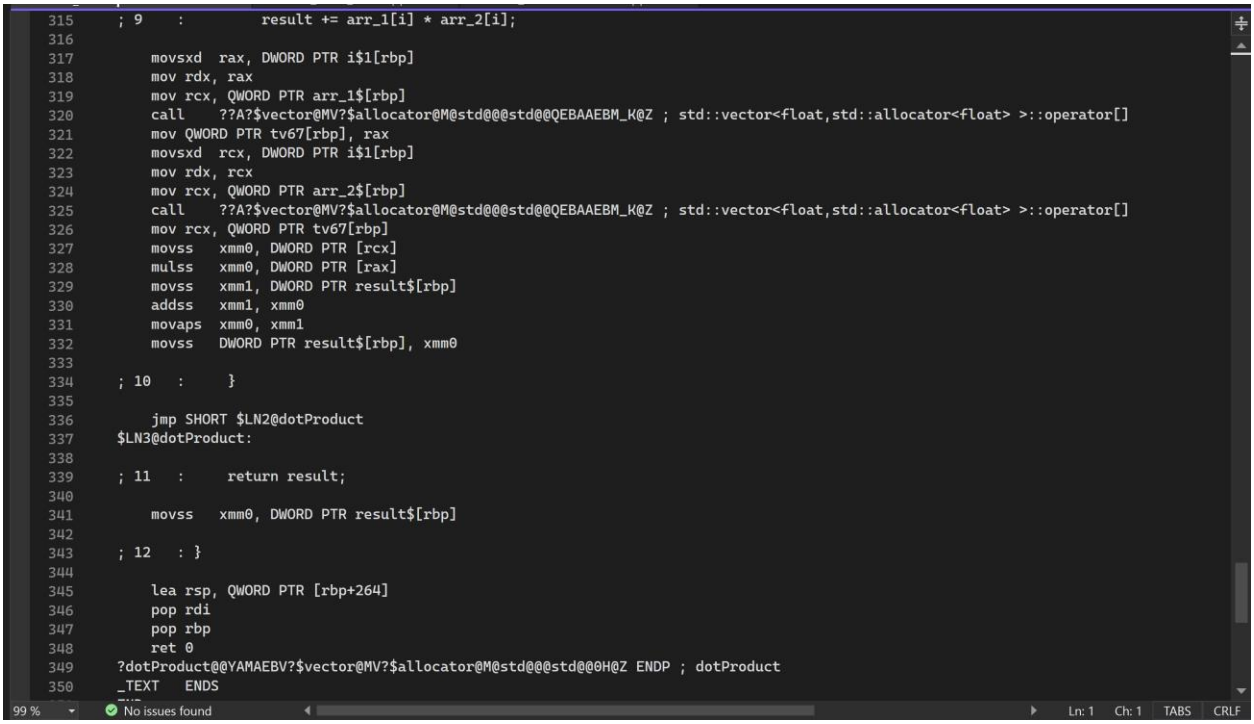
Figure 46 - asm file for dotProduct.cpp - non-Optimized for dotProduct

Non-Optimized complete Assembly Code

Below we can see the complete non-optimized assembly Code.

```
282     ; 4    : float dotProduct(const std::vector<float>& arr_1, const std::vector<float>& arr_2, const int size) {
283
284     $LN6:
285         mov DWORD PTR [rsp+24], r8d
286         mov QWORD PTR [rsp+16], rdx
287         mov QWORD PTR [rsp+8], rcx
288         push    rbp
289         push    rdi
290         sub rsp, 312                ; 00000138H
291         lea rbp, QWORD PTR [rsp+48]
292         lea rcx, OFFSET FLAT:__D0D3A000_Peiravani_Paniz_dotProduct@cpp
293         call    __CheckForDebuggerJustMyCode
294
295     ; 5    :     float result = 0;
296
297         xorps   xmm0, xmm0
298         movss   DWORD PTR result$[rbp], xmm0
299
300     ; 6    :
301     ; 7    :     // Iterate through both vectors and calculate the dot product
302     ; 8    :     for (int i = 0; i < size; i++) {
303
304         mov DWORD PTR i$1[rbp], 0
305         jmp SHORT $LN4@dotProduct
306     $LN2@dotProduct:
307         mov eax, DWORD PTR i$1[rbp]
308         inc eax
309         mov DWORD PTR i$1[rbp], eax
310     $LN4@dotProduct:
311         mov eax, DWORD PTR size$[rbp]
312         cmp DWORD PTR i$1[rbp], eax
313         jge SHORT $LN3@dotProduct
314
315     ; 9    :         result += arr_1[i] * arr_2[i];
316
```

Figure 47 - O1 Assembly Code on Windows



```
315     ; 9    :         result += arr_1[i] * arr_2[i];
316
317         movsxd  rax, DWORD PTR i$1[rbp]
318         mov rdx, rax
319         mov rcx, QWORD PTR arr_1$[rbp]
320         call    ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ; std::vector<float,std::allocator<float> >::operator[]
321         mov QWORD PTR tv67[rbp], rax
322         movsxd  rcx, DWORD PTR i$1[rbp]
323         mov rdx, rcx
324         mov rcx, QWORD PTR arr_2$[rbp]
325         call    ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ; std::vector<float,std::allocator<float> >::operator[]
326         mov rcx, QWORD PTR tv67[rbp]
327         movss   xmm0, DWORD PTR [rcx]
328         mulss   xmm0, DWORD PTR [rax]
329         movss   xmm1, DWORD PTR result$[rbp]
330         addss   xmm1, xmm0
331         movaps  xmm0, xmm1
332         movss   DWORD PTR result$[rbp], xmm0
333
334     ; 10   :     }
335
336         jmp SHORT $LN2@dotProduct
337     $LN3@dotProduct:
338
339     ; 11   :     return result;
340
341         movss   xmm0, DWORD PTR result$[rbp]
342
343     ; 12   : }
344
345         lea rsp, QWORD PTR [rbp+264]
346         pop rdi
347         pop rbp
348         ret 0
349     ?dotProduct@@YAMAEBV?$vector@MV?$allocator@M@std@@@std@@0H@Z ENDP ; dotProduct
350     _TEXT   ENDS
```

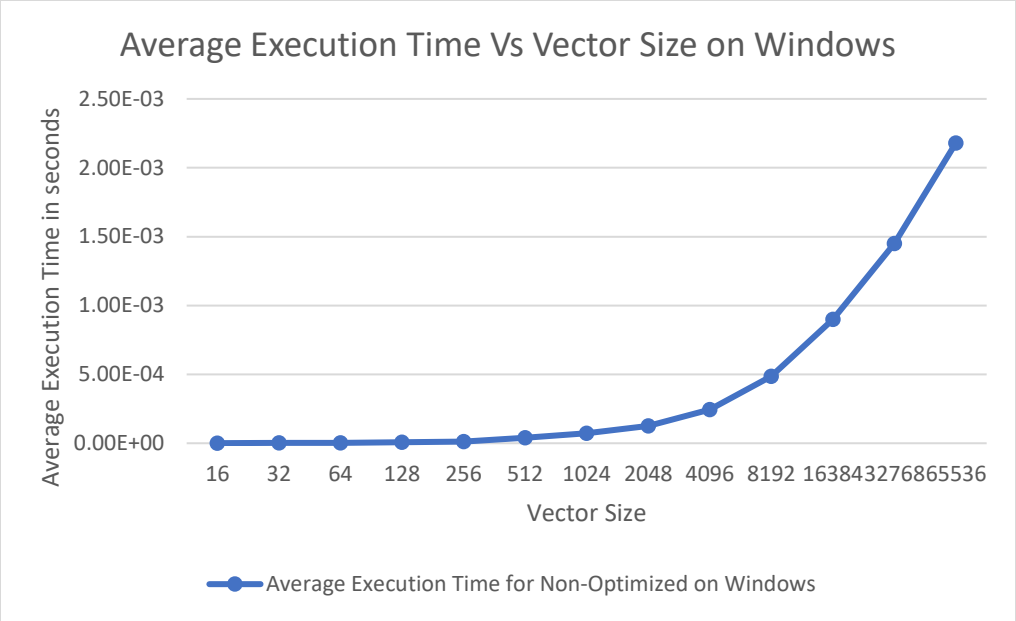
99 % No issues found Ln: 1 Ch: 1 TABS CRLF

Figure 48 - O1 Assembly Code on Windows

Graph

Table 4 - Non-Optimized Execution in second for windows

Vector Size	Execution time for Non-Optimized on Windows
16	8.20E-07
32	2.04E-06
64	3.84E-06
128	6.71E-06
256	1.28E-05
512	4.05E-05
1024	7.33E-05
2048	1.25E-04
4096	2.44E-04
8192	4.87E-04
16384	9.00E-04
32768	1.45E-03
65536	2.18E-03



Graph 3 - Non-Optimized Execution in second for windows

Compiler Optimization

First, we need to enable Automatic Parallelization, /Qpar, and Automatic Vectorization, /arch. We can enable them like how we disable them in task 2. To enable automatic parallelization and automatic vectorization, we need to go to the project properties. In order to get to the project properties, we need to right-click on our project name.

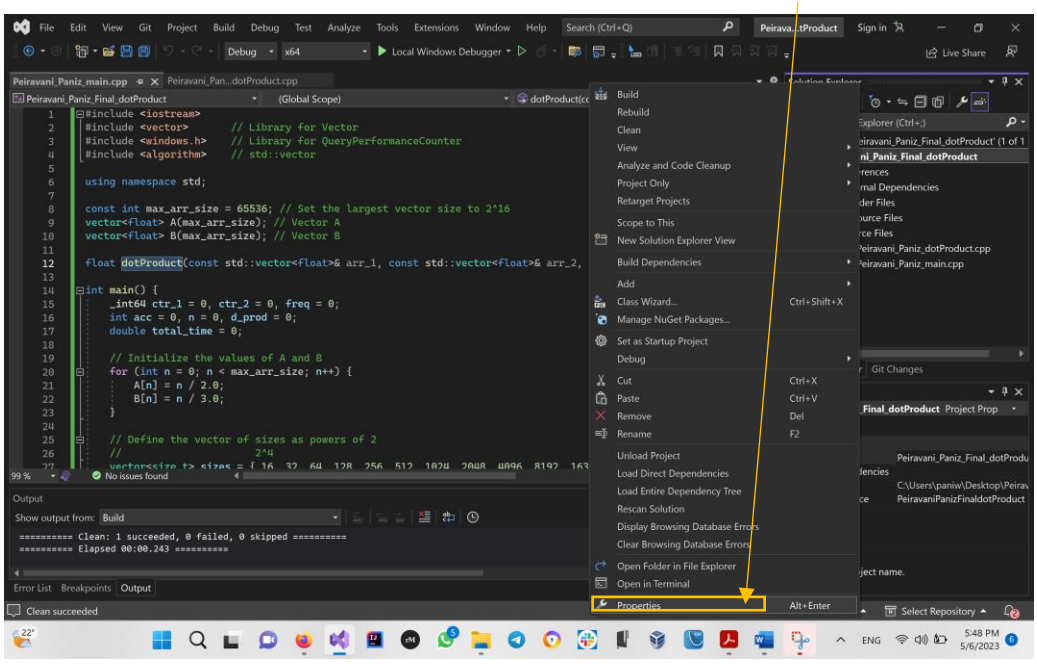


Figure 49 – Project Properties on VS – windows

Once we are in project properties, we can use the steps below to enable Parallel Code Generation and Enhanced Instruction Set.

Project Property, C/C++, Code Generation, and enable Parallel Code Generation by using *Yes (/Qpar)* and enable Enhanced Instruction Set by using *Yes Enhanced Instructions (/arch:AVX)* and then press apply. Based on our task 1, I know that my hardware can handle AVX.

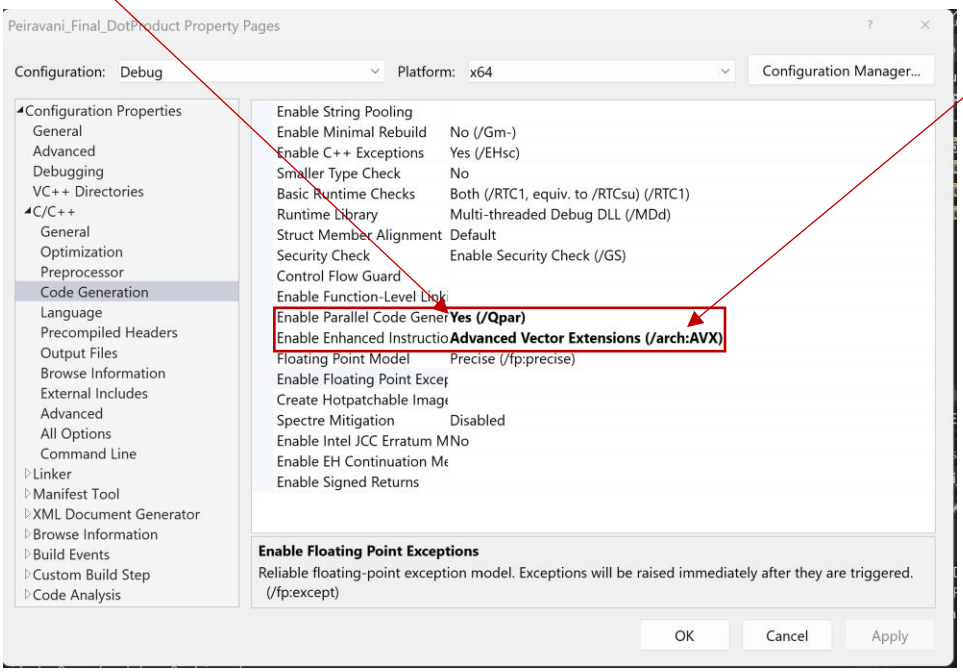


Figure 50 - enable Parallel Code Generation and Enhanced Instruction Set on VS – Windows

And choose *optimization* on optimization section on Visual Studio. We will one time choose O1 which is good for size and O2 which is good for speed.

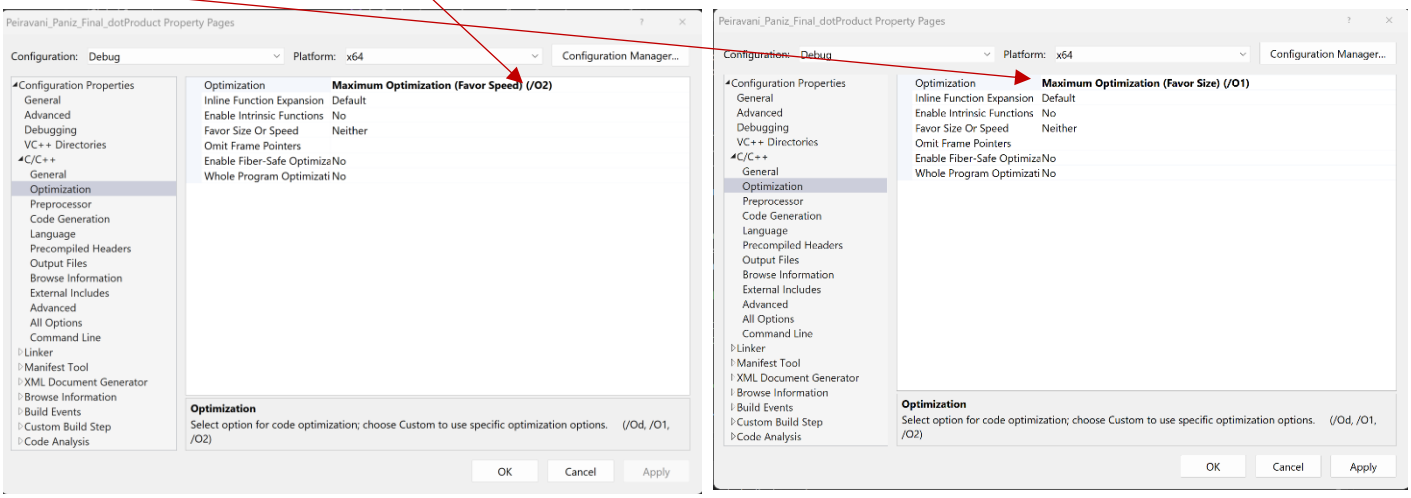


Figure 51 – Compiler Optimization on VS

O1 - Optimization

Once we build our code, we can go to the project folder, and we will see .asm output which is optimized for O1.

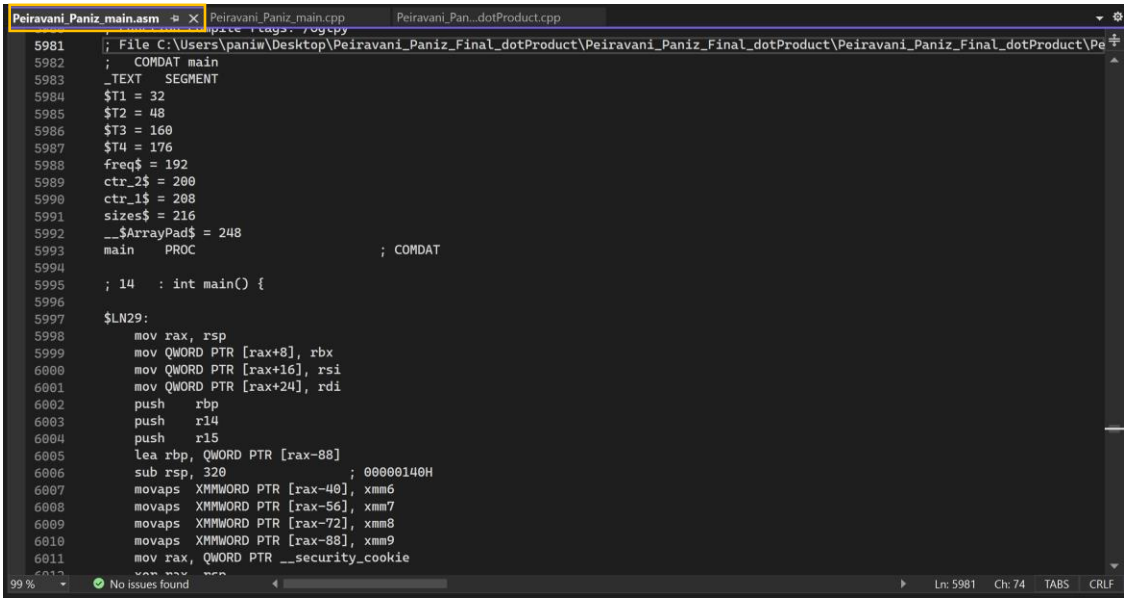


Figure 52 - O1 optimized code for main.cpp

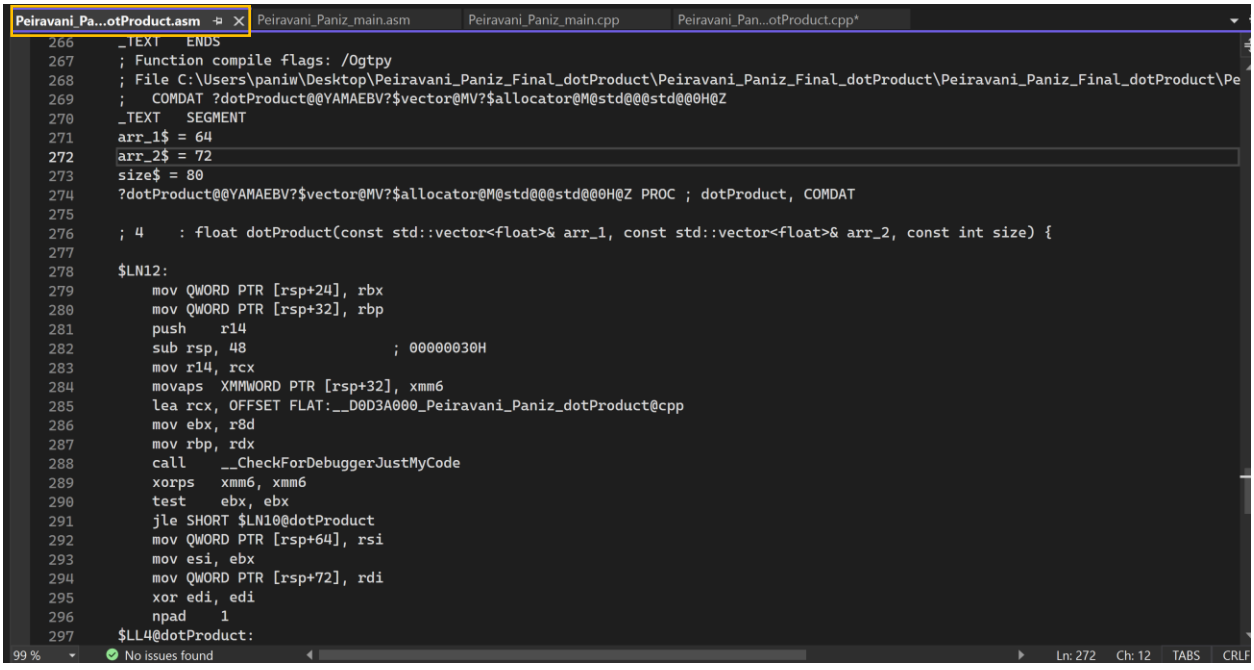


Figure 53 - O1 optimized code for dorProduct.cpp

We can see that our assembly is using vectorization since we enable it.

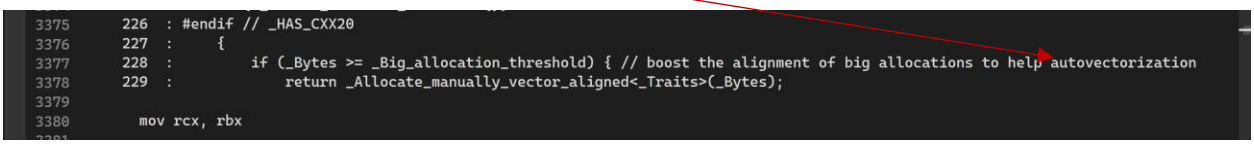


Figure 54 – vectorization

And our code is shorter than non-optimized. We can compare the blue box in in *Figure 45* for main.cpp and green box on *Figure 46* for dotProduct.cpp to see the difference.

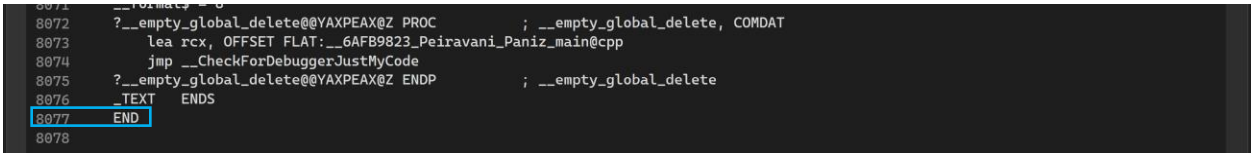


Figure 55 – O1 optimized code for main.cpp

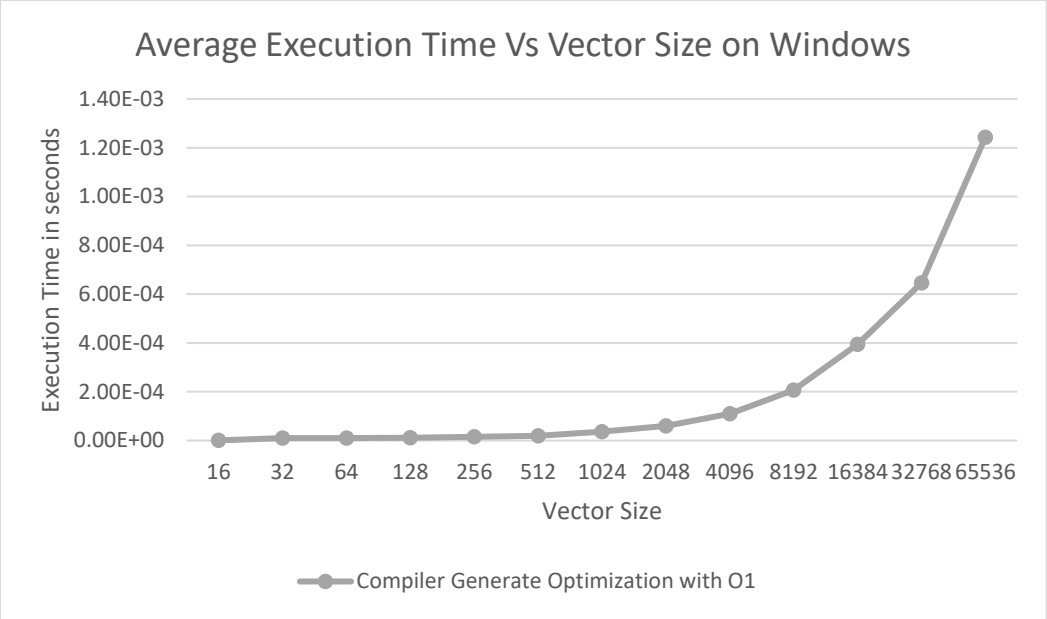
Figure 56 - O1 optimized code for dotProduct.cpp

Graph

On the Table and graph below, we can see the execution in Windows time for O1 optimization after we run the code.

Table 5 – Execution time for Compiler Generated Optimization with O1

Vector Size	Execution time in second for Compiler Generated Optimization with O1
16	6.90E-07
32	9.97E-06
64	1.08E-05
128	1.17E-05
256	1.50E-05
512	2.00E-05
1024	3.64E-05
2048	6.06E-05
4096	1.10E-04
8192	2.07E-04
16384	3.95E-04
32768	6.46E-04
65536	1.24E-03



Graph 4 - Execution time for Compiler Generated Optimization with O1

Complete Assembly Code for O1

Below we can see the O1 optimization complete assembly Code in Windows Intel x64.

```
Peiravani_Pan...imization.asm | Peiravani_Paniz_main.asm | Peiravani_Paniz_main.cpp | Peiravani_Pan...dotProduct.cpp
276     ; 4    : float dotProduct(const std::vector<float>& arr_1, const std::vector<float>& arr_2, const int size) {
277
278     $LN12:
279         mov QWORD PTR [rsp+24], rbx
280         mov QWORD PTR [rsp+32], rbp
281         push    r14
282         sub rsp, 48                 ; 00000030H
283         mov r14, rcx
284         movaps  XMMWORD PTR [rsp+32], xmm6
285         lea rcx, OFFSET FLAT:__D0D3A000_Peiravani_Paniz_dotProduct@cpp
286         mov ebx, r8d
287         mov rbp, rdx
288         call    __CheckForDebuggerJustMyCode
289         xorps   xmm6, xmm6
290         test    ebx, ebx
291         jle SHORT $LN10@dotProduct
292         mov QWORD PTR [rsp+64], rsi
293         mov esi, ebx
294         mov QWORD PTR [rsp+72], rdi
295         xor edi, edi
296         npad    1
297     $LL4@dotProduct:
298
299     ; 5    :     float result = 0;
300     ; 6    :
301     ; 7    :     // Iterate through both vectors and calculate the dot product
302     ; 8    :     for (int i = 0; i < size; i++) {
303     ; 9    :         result += arr_1[i] * arr_2[i];
304
305         mov rdx, rdi
306         mov rcx, r14
307         call    ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ; std::vector<float,std::allocator<float> >::operator[]
308         mov rdx, rdi
309         mov rcx, rbp
310         mov rbx, rax
311         call    ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ; std::vector<float,std::allocator<float> >::operator[]
```

Figure 57 - Complete Assembly Code for O1

```
311         call    ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ; std::vector<float,std::allocator<float> >::operator[]
312         movss   xmm1, DWORD PTR [rbx]
313         inc rdi
314         mulss   xmm1, DWORD PTR [rax]
315         addss   xmm6, xmm1
316         sub rsi, 1
317         jne SHORT $LL4@dotProduct
318
319     ; 10   :     }
320     ; 11   :     return result;
321
322         mov rdi, QWORD PTR [rsp+72]
323         movaps  xmm0, xmm6
324         mov rsi, QWORD PTR [rsp+64]
325         jmp SHORT $LN3@dotProduct
326     $LN10@dotProduct:
327         xorps   xmm0, xmm0
328     $LN3@dotProduct:
329
330     ; 12   : }
331
332         mov rbx, QWORD PTR [rsp+80]
333         mov rbp, QWORD PTR [rsp+88]
334         movaps  xmm6, XMMWORD PTR [rsp+32]
335         add rsp, 48                 ; 00000030H
336         pop r14
337         ret 0
338     ?dotProduct@@YAMAEBV?$vector@MV?$allocator@M@std@@@std@@0H@Z ENDP ; dotProduct
339     _TEXT   ENDS
340     END
```

99 % No issues found Ln: 1 Ch: 1 TABS CRLF

Figure 58 - Complete Assembly Code for O1

O2 - Optimization

Now we can build our code for O2 to see .asm assembly code for O2.

```
5964    ; Function compile flags: /Ogspy
5965    ; File C:\Users\paniw\Desktop\Peiravani_Paniz_Final_dotProduct\Peiravani_Paniz_Final_dotProduct\Peiravani_Paniz_Final_dotProduct\Peira
5966    ;   COMDAT main
5967    _TEXT   SEGMENT
5968    $T1 = 32
5969    $T2 = 48
5970    $T3 = 160
5971    $T4 = 176
5972    freq$ = 192
5973    ctr_2$ = 200
5974    ctr_1$ = 208
5975    sizes$ = 216
5976    __$ArrayPad$ = 248
5977    main    PROC                        ; COMDAT
5978
5979    ; 14   : int main() {
5980
5981    $LN29:
5982        mov rax, rsp
5983        mov QWORD PTR [rax+8], rbx
5984        mov QWORD PTR [rax+16], rsi
5985        mov QWORD PTR [rax+24], rdi
5986        mov QWORD PTR [rax+32], r13
5987        push    rbp
5988        push    r14
5989        push    r15
5990        lea rbp, QWORD PTR [rax-56]
5991        sub rsp, 288                ; 00000120H
5992        movaps  XMMWORD PTR [rax-40], xmm6
5993        movaps  XMMWORD PTR [rax-56], xmm7
5994        mov rax, QWORD PTR __security_cookie
5995        xor rax, rsp
5996        mov QWORD PTR   $ArrayPad$[rbp-256], rax
```

Peiravani_Paniz_main.asm | Peiravani_Pan...dotProduct.asm | Peiravani_Paniz_main.cpp | Peiravani_Pan...dotProduct.cpp

99 % No issues found Ln: 5965 Ch: 110 TABS CRLF

Output — Show output from: Build

Figure 59 – O2 optimized code for main.cpp

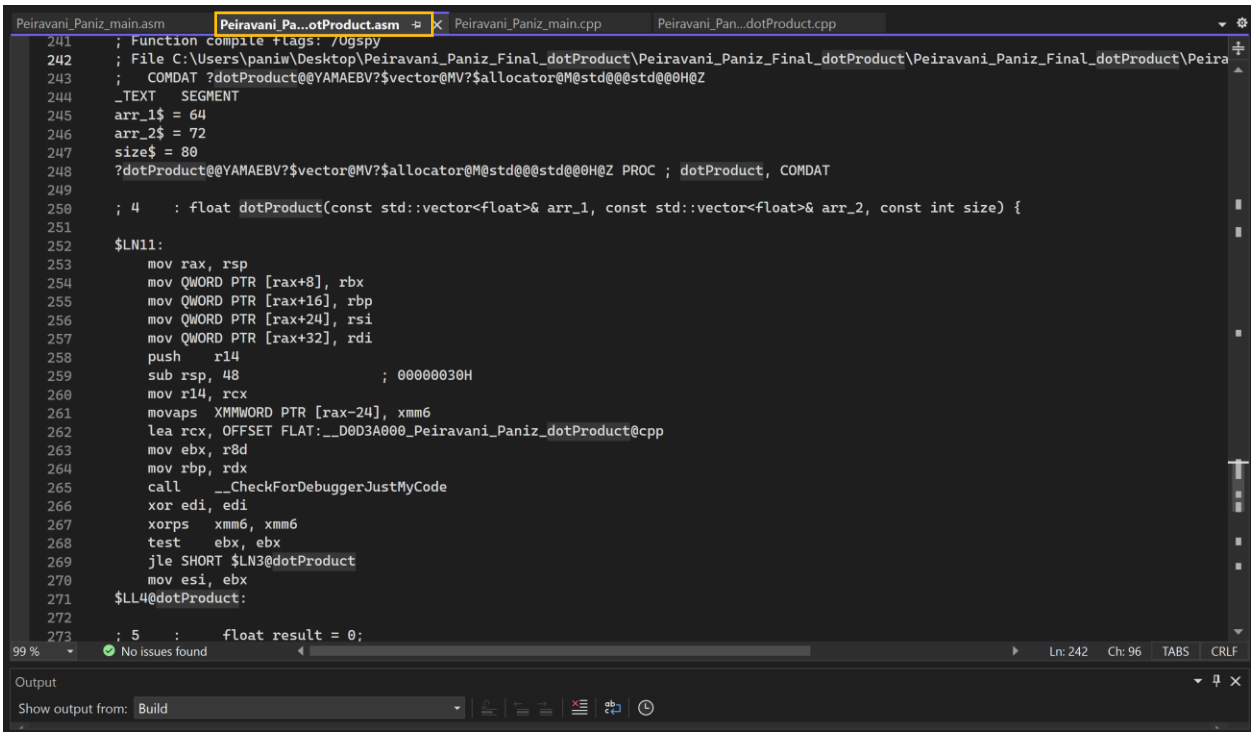


Figure 60 – O2 optimized code for dotProduct.cpp

We can see that our assembly is using vectorization since we enable it.

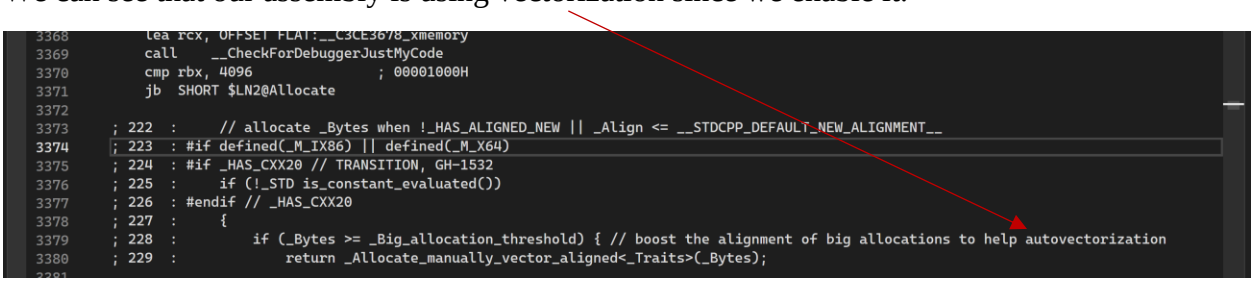


Figure 61 - Vectorization

And our code is shorter than non-optimized and O1 optimization. We can compare green box on *Figure 45* for main.cpp and green box on *Figure 46* for dotProduct.cpp to see the difference.

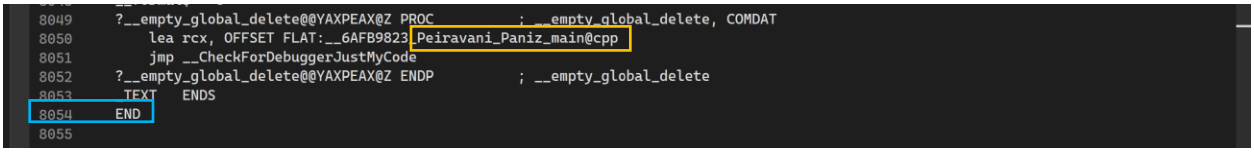


Figure 62 – O2 optimized code for main.cpp

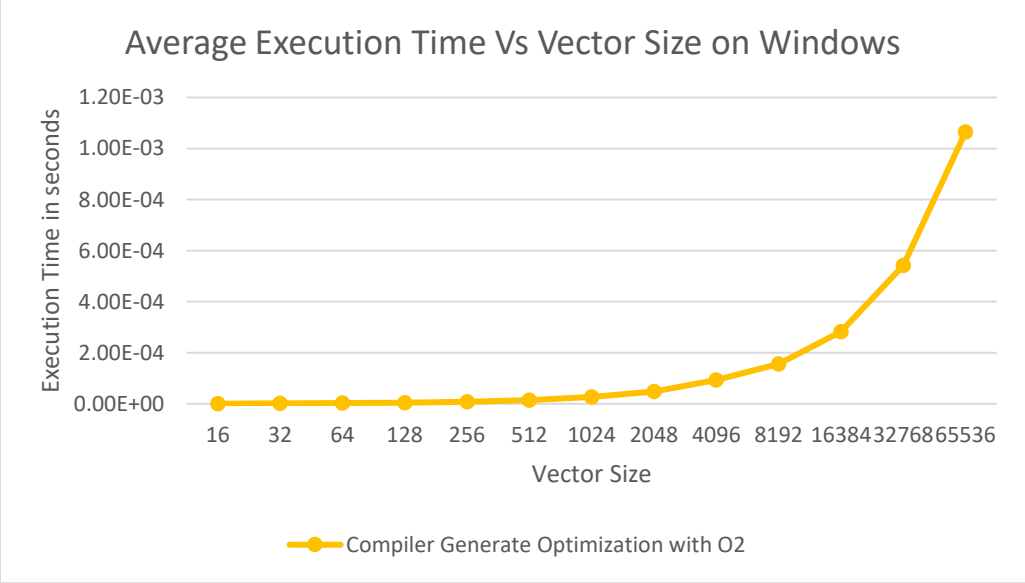
Figure 63 - O2 optimized code for dorProduct.cpp

Graph

On Table and graph below, we can see the execution time in Windows for O2 optimization after we run the code.

Table 6 - Execution time for Compiler Generated Optimization with O2

Vector Size	Execution time in second for Compiler Generate Optimization with O2
16	6.60E-07
32	1.55E-06
64	2.88E-06
128	4.64E-06
256	8.25E-06
512	1.44E-05
1024	2.68E-05
2048	4.82E-05
4096	9.27E-05
8192	1.57E-04
16384	2.82E-04
32768	5.42E-04
65536	1.06E-03



Graph 5 - Execution time for Compiler Generated Optimization with O2

Complete O2 Optimization Code

Below we can see the O2 optimization complete assembly Code in Windows Intel x64.

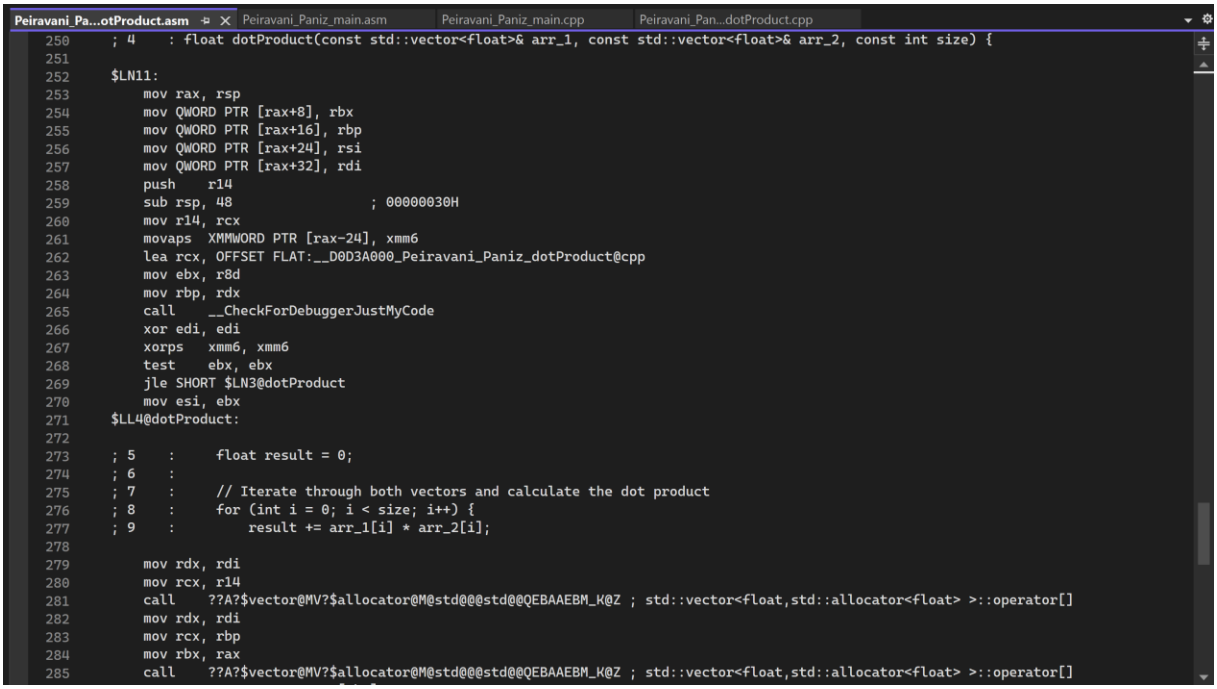


Figure 64 - O2 Assembly Code on Windows

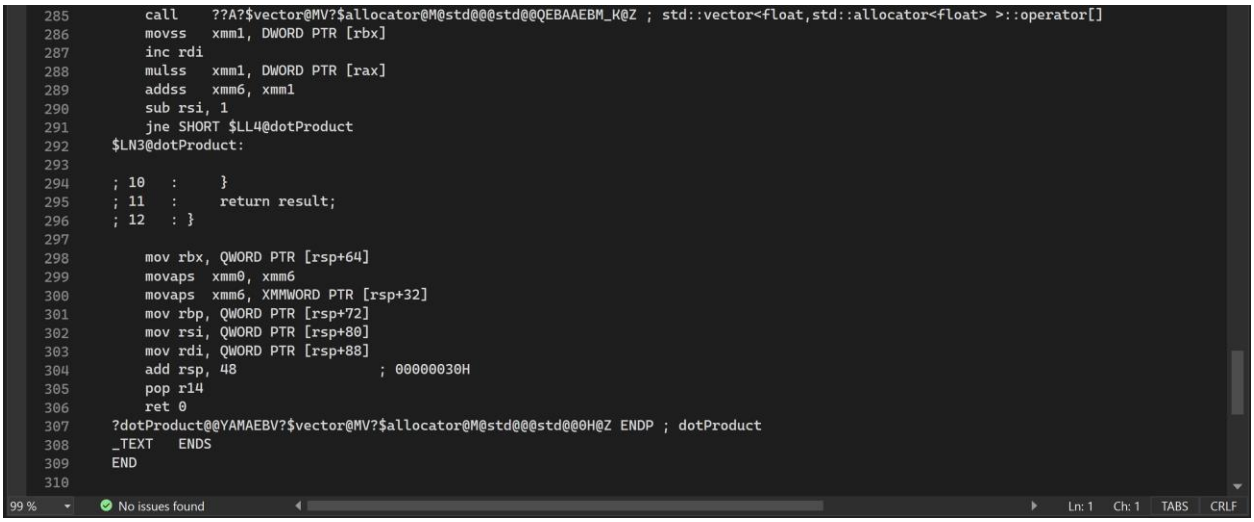


Figure 65 - O2 Assembly Code on Windows

Manually Optimization

Now we are manually optimizing the code that we. The red lines show the code that I can remove and the green lines the code that I optimized. One way to optimize is to reduce the use of `mov` instructions by reusing registers or rearranging instructions and changing bytes storage for memory usage and speed.

```
; 4    : float dotProduct(const std::vector<float>& arr_1, const std::vector<float>&
arr_2, const int size) {

$LN11:
       mov    rax, rsp

       mov    QWORD PTR [rax+8], rbx
mov    QWORD PTR [rsp+24], rbx         //rsp = to stack pointer register and change
                                         the bytes
       mov    QWORD PTR [rax+16], rbp
       mov    QWORD PTR [rsp+32], rbp         //rsp = to stack pointer register and
                                                change bytes
       mov    QWORD PTR [rax+24], rsi
       mov    QWORD PTR [rsp+32], rdi         //rsp = to stack pointer register and
                                                change the bytes
       push   r14
       sub    rsp, 48                                ; 00000030H
       mov    r14, rcx
       movaps XMMWORD PTR [rax-24], xmm6
       movaps XMMWORD PTR [rax+32], xmm6      //rsp = to stack pointer register and
                                                change the bytes
       lea    rcx, OFFSET FLAT:__D0D3A000_Peiravani_Paniz_dotProduct@cpp
       mov    ebx, r8d
       mov    rbp, rdx
       call   __CheckForDebuggerJustMyCode
       xorps  xmm6, xmm6
       test   ebx, ebx
       jle    SHORT $LN3@dotProduct
       mov        QWORD PTR [rsp+64], rsi
       mov        esi, ebx
       mov        esi, ebx
       mov        QWORD PTR [rsp+72], rdi
       xor        edi, ed
       mov    esi, ebx
$LL4@dotProduct:

; 5    :     float result = 0;
; 6    :
; 7    :     // Iterate through both vectors and calculate the dot product
; 8    :     for (int i = 0; i < size; i++) {
; 9    :         result += arr_1[i] * arr_2[i];

       mov    rdx, rdi
       mov    rcx, r14
       call   ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ;
std::vector<float,std::allocator<float> >::operator[]
       mov    rdx, rdi
       mov    rcx, rbp
       mov    rbx, rax
       call   ??A?$vector@MV?$allocator@M@std@@@std@@QEBAAEBM_K@Z ;
std::vector<float,std::allocator<float> >::operator[]
```

```
        movss  xmm1, DWORD PTR [rbx]
        inc    rdi
        mulss  xmm1, DWORD PTR [rax]
        addss  xmm6, xmm1
        sub    rsi, 1
        jne    SHORT $LL4@dotProduct
$LN3@dotProduct:

; 10   :     }
; 11   :     return result;
        Mov    rdi, QWORD PTR [rsp+72]
        mov    rdi, QWORD PTR [rsp+72]
        mov    rsi, QWORD PTR [rsp+64]
        mov    rsi, QWORD PTR [rsp+80]

        vmovaps        xmm0, xmm6
        jmp        SHORT $LN3@dotProduct

$LN10@dotProduct:
        vxorps         xmm0, xmm0, xmm0

$LN3@dotProduct:
; 12   : }

        mov    rbx, QWORD PTR [rsp+64]
        mov    rbx, QWORD PTR [rsp+80]
        movaps xmm0, xmm6
        movaps xmm6, XMMWORD PTR [rsp+32]
        mov    rbp, QWORD PTR [rsp+72]
        mov    rbx, QWORD PTR [rsp+88]
        mov    rsi, QWORD PTR [rsp+80]
        mov    rdi, QWORD PTR [rsp+88]
        add    rsp, 48                                 ; 00000030H
        pop    r14
        ret    0
?dotProduct@@YAMAEBV?$vector@MV?$allocator@M@std@@@std@@@0H@Z ENDP ; dotProduct
_TEXT  ENDS
END
```

Now here is my final optimization code.

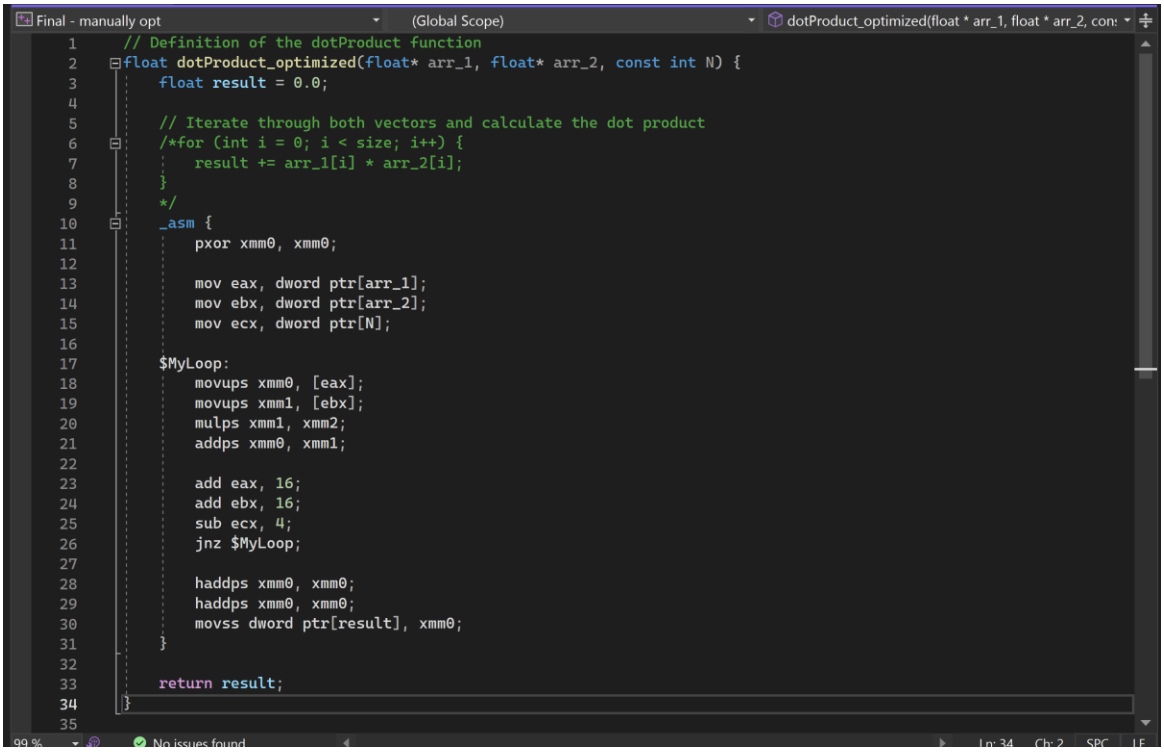


Figure 66 - Manually Optimize

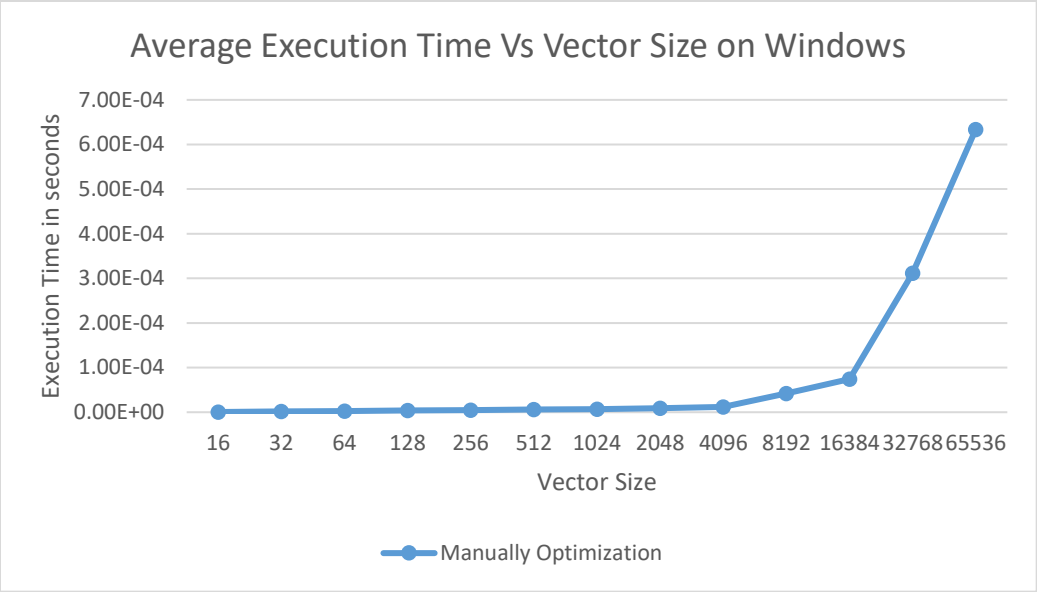
And after we run the code, we can see that the execution time is less than before. Below table shows the execution time of our manually optimization code.

Graph

On the Table and graph below, we can see the execution time in Windows for manually optimization after we run the code.

Table 7 – Execution time for Manually Optimization

Vector Size	Execution time in second for Manually Optimization
16	4.70E-07
32	1.97E-06
64	2.46E-06
128	4.19E-06
256	4.90E-06
512	6.05E-06
1024	7.15E-06
2048	9.10E-06
4096	1.16E-05
8192	4.23E-05
16384	7.45E-05
32768	3.12E-04
65536	6.34E-04

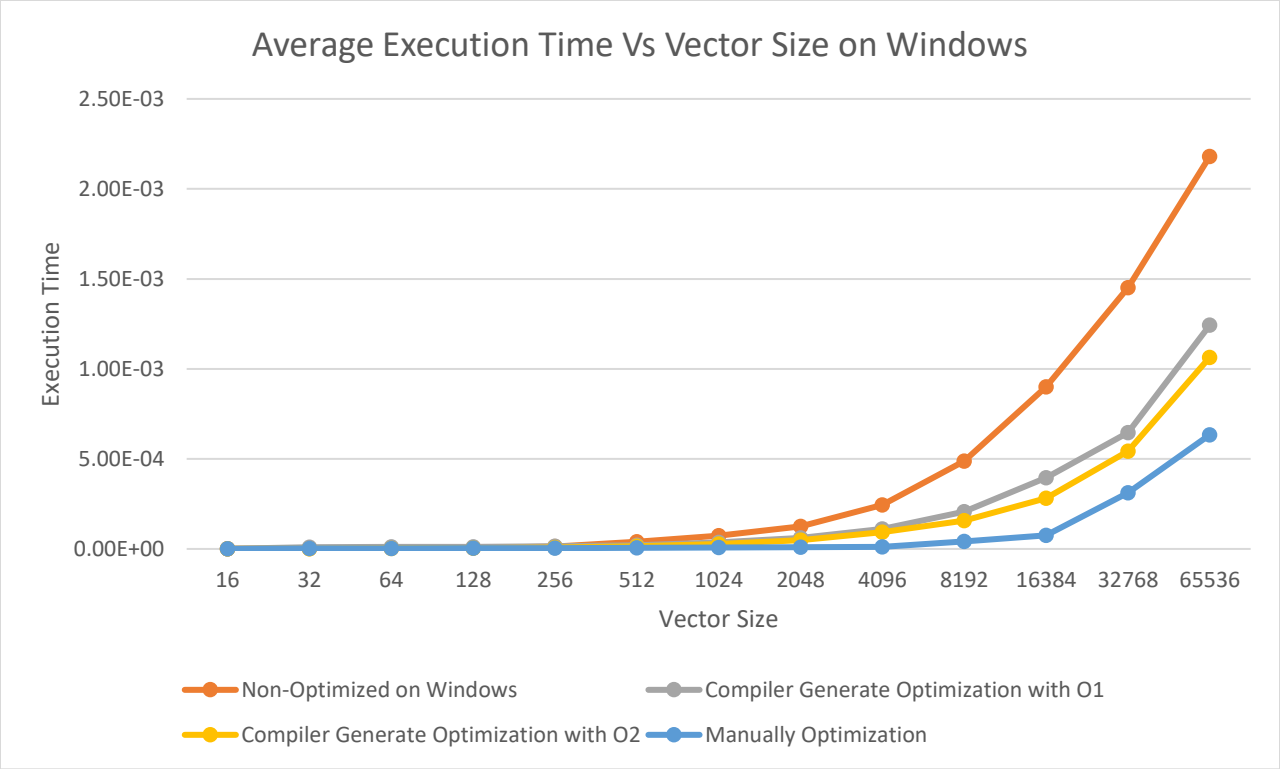


Graph

Now that we have our execution time for non-optimized, O1 optimization, O2 optimization, and manually optimization we can put the execution time on graph to compare the executions times in Windows Intel x64. We ran the code 10 times for each vector size to be able to find the average execution time that is more accurate.

Table 8 - Task 3 for Windows

Vector Size	Non-Optimized on Windows	Compiler Generate Optimization with O1	Compiler Generate Optimization with O2	Manually Optimization
16	8.20E-07	6.90E-07	6.60E-07	4.70E-07
32	2.04E-06	9.97E-06	1.55E-06	1.97E-06
64	3.84E-06	1.08E-05	2.88E-06	2.46E-06
128	6.71E-06	1.17E-05	4.64E-06	4.19E-06
256	1.28E-05	1.50E-05	8.25E-06	4.90E-06
512	4.05E-05	2.00E-05	1.44E-05	6.05E-06
1024	7.33E-05	3.64E-05	2.68E-05	7.15E-06
2048	1.25E-04	6.06E-05	4.82E-05	9.10E-06
4096	2.44E-04	1.10E-04	9.27E-05	1.16E-05
8192	4.87E-04	2.07E-04	1.57E-04	4.23E-05
16384	9.00E-04	3.95E-04	2.82E-04	7.45E-05
32768	1.45E-03	6.46E-04	5.42E-04	3.12E-04
65536	2.18E-03	1.24E-03	1.06E-03	6.34E-04



Graph 6 - Task 3 for windows

Linux – Ubuntu

Non-Optimized Assembly Code

The Automatic Parallelization, Automatic Vectorization, and optimization from previous task 2 still disable. To get the Non-Optimized assembly code, we can use the below command line on Ubuntu gcc. We will use the disabled flags for Automatic Parallelization, Automatic Vectorizatjust to be sure.

```
// The -fno-tree-vectorize flag disables automatic vectorization.

// The -fno-tree-loop-distribute-patterns flag disables automatic loop

// The -O0 will make sure that the code stays unoptimized

// -S will create a file for the assembly code
```

```
g++ -O0 -fno-tree-loop-distribute-patterns -fno-tree-vectorize
Peiravani_Paniz_dotProduct.cpp -o Peiravani_Paniz_dotProduct_NonOpt -S
```

```
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ g++ -O0 -fno-tree-loop-distribute-patterns -fno-tree-vectorize
Peiravani_Paniz_dotProduct.cpp -o Peiravani_Paniz_dotProduct_NonOpt -S
```

Figure 67 – Non-Optimized Assembly code

Complete Non-Optimized Assembly Code

Now terminal will make a file in our project folder that contains non-optimized assembly code for out C++ code.

```
        .file   "Peiravani_Paniz_dotProduct.cpp"
        .text
        .p2align 4
        .globl  _Z10dotProductRKSt6vectorIfSaIfEES3_i
        .type   _Z10dotProductRKSt6vectorIfSaIfEES3_i, @function
_Z10dotProductRKSt6vectorIfSaIfEES3_i:
.LFB865:
        .cfi_startproc
        endbr64
        testl   %edx, %edx
        jle     .L10
        leal    -1(%rdx), %eax
        movq    (%rdi), %rdi
        movq    (%rsi), %rcx
        cmpl    $6, %eax
        jbe     .L11
        movl    %edx, %esi
        xorl    %eax, %eax
        vxorps  %xmm0, %xmm0, %xmm0
        shrl    $3, %esi
        salq    $5, %rsi
        .p2align 4,,10
        .p2align 3
.L4:
        vmovups (%rdi,%rax), %ymm4
        vmulps  (%rcx,%rax), %ymm4, %ymm1
        addq    $32, %rax
        vaddss  %xmm1, %xmm0, %xmm0
        vshufps $85, %xmm1, %xmm1, %xmm3
        vshufps $255, %xmm1, %xmm1, %xmm2
        vaddss  %xmm3, %xmm0, %xmm0
        vunpckhps       %xmm1, %xmm1, %xmm3
```

Figure 68 - Non-Optimized on Linux

```
        vextractf128    $0x1, %ymm1, %xmm1
        vaddss  %xmm3, %xmm0, %xmm0
        vaddss  %xmm2, %xmm0, %xmm0
        vshufps $85, %xmm1, %xmm1, %xmm2
        vaddss  %xmm1, %xmm0, %xmm0
        vaddss  %xmm2, %xmm0, %xmm0
        vunpckhps       %xmm1, %xmm1, %xmm2
        vshufps $255, %xmm1, %xmm1, %xmm1
        vaddss  %xmm2, %xmm0, %xmm0
        vaddss  %xmm1, %xmm0, %xmm0
        cmpq    %rsi, %rax
        jne     .L4
        movl    %edx, %esi
        andl    $-8, %esi
        movl    %esi, %eax
        cmpl    %esi, %edx
        je      .L16
        vzeroupper
.L3:
        movl    %edx, %r8d
        subl    %esi, %r8d
        leal    -1(%r8), %r9d
        cmpl    $2, %r9d
        jbe     .L7
        vmovups (%rdi,%rsi,4), %xmm5
        vmulps  (%rcx,%rsi,4), %xmm5, %xmm1
        movl    %r8d, %esi
        andl    $-4, %esi
        addl    %esi, %eax
        vaddss  %xmm1, %xmm0, %xmm0
        vshufps $85, %xmm1, %xmm1, %xmm2
        vaddss  %xmm2, %xmm0, %xmm0
        vunpckhps       %xmm1, %xmm1, %xmm2
```

Figure 69 - Non-Optimized on Linux

```
65          vunpckhps       %xmm1, %xmm1, %xmm2
66          vshufps $255, %xmm1, %xmm1, %xmm1
67          vaddss  %xmm2, %xmm0, %xmm0
68          vaddss  %xmm1, %xmm0, %xmm0
69          cmpl    %esi, %r8d
70          je      .L1
71  .L7:
72          cltq
73          .p2align 4,,10
74          .p2align 3
75  .L9:
76          vmovss  (%rdi,%rax,4), %xmm1
77          vmulss  (%rcx,%rax,4), %xmm1, %xmm1
78          addq    $1, %rax
79          vaddss  %xmm1, %xmm0, %xmm0
80          cmpl    %eax, %edx
81          jg      .L9
82          ret
83          .p2align 4,,10
84          .p2align 3
85  .L10:
86          vxorps  %xmm0, %xmm0, %xmm0
87  .L1:
88          ret
89          .p2align 4,,10
90          .p2align 3
91  .L16:
92          vzeroupper
93          ret
94  .L11:
95          xorl    %esi, %esi
96          xorl    %eax, %eax
```

Figure 70 - Non-Optimized on Linux

```
96          xorl    %eax, %eax
97          vxorps  %xmm0, %xmm0, %xmm0
98          jmp     .L3
99          .cfi_endproc
100 .LFE865:
101         .size   _Z10dotProductRKSt6vectorIfSaIfEES3_i, .-_Z10dotProductRKSt6vectorIfSaIfEES3_i
102         .ident  "GCC: (Ubuntu 11.3.0-1ubuntu1~22.04) 11.3.0"
103         .section        .note.GNU-stack,"",@progbits
104         .section        .note.gnu.property,"a"
105         .align 8
106         .long   1f - 0f
107         .long   4f - 1f
108         .long   5
109 0:
110         .string "GNU"
111 1:
112         .align 8
113         .long   0xc0000002
114         .long   3f - 2f
115 2:
116         .long   0x3
117 3:
118         .align 8
119 4:
```

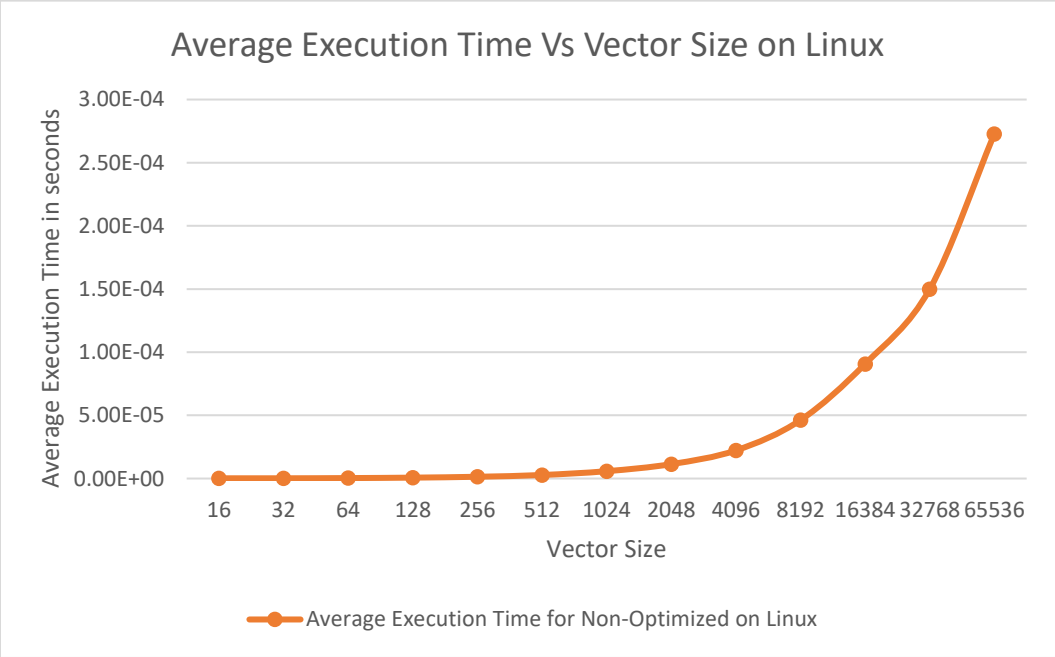
Figure 71 - Non-Optimized on Linux

Graph

On the Table and graph below, we can see the execution time in Linux for non-optimization after we run the code.

Table 9 – non-optimized assembly execution time on Linbux

Vector Size	Execution time in seconds for Non-Optimized on Windows
16	2.28E-07
32	2.17E-07
64	3.97E-07
128	7.36E-07
256	1.43E-06
512	2.82E-06
1024	5.83E-06
2048	1.14E-05
4096	2.23E-05
8192	4.63E-05
16384	9.07E-05
32768	1.50E-04
65536	2.73E-04



Graph 7 - non-optimized assembly execution time on Linbux

Compiler Optimization

O1 - Optimization

First, we need to enable Automatic Parallelization, /Qpar, and Automatic Vectorization, /arch. For enabling automatic parallelization and automatic vectorization we can use the below command line on Ubuntu gcc.

```
// The -ftree-vectorize flag eables automatic vectorization.

// The -ftree-loop-distribute-patterns flag eables automatic loop parallelization.

// The -O1 has level 1 optimization which is basic

// -mavx is for AVX vector instructor

// -S will create a file for the assembly code

g++ -O1 -ftree-loop-distribute-patterns -ftree-vectorize -mavx
Peiravani_Paniz_dotProduct.cpp -o Peiravani_Paniz_dotProduct_OptO1 -S
```

```
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ g++ -O1 -ftree-loop-distribute-patterns
-ftree-vectorize -mavx Peiravani_Paniz_dotProduct.cpp -o Peiravani_Paniz_dotProduct_OptO1 -S
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$
```

Figure 72 – get Assembly O1 optimize on Linux

After we run the O1 optimized code, we can see the execution time is less than from non-Optimized.

```
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ g++ -O1 -ftree-loop-distribute-patterns
-ftree-vectorize -mavx Peiravani_Paniz_main.cpp Peiravani_Paniz_dotProduct.cpp -o Peiravani_Pa
niz_dotProduct_OptO1
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ ./Peiravani_Paniz_dotProduct_OptO1
```

Figure 73 – run the C++ code with O1 Optimization

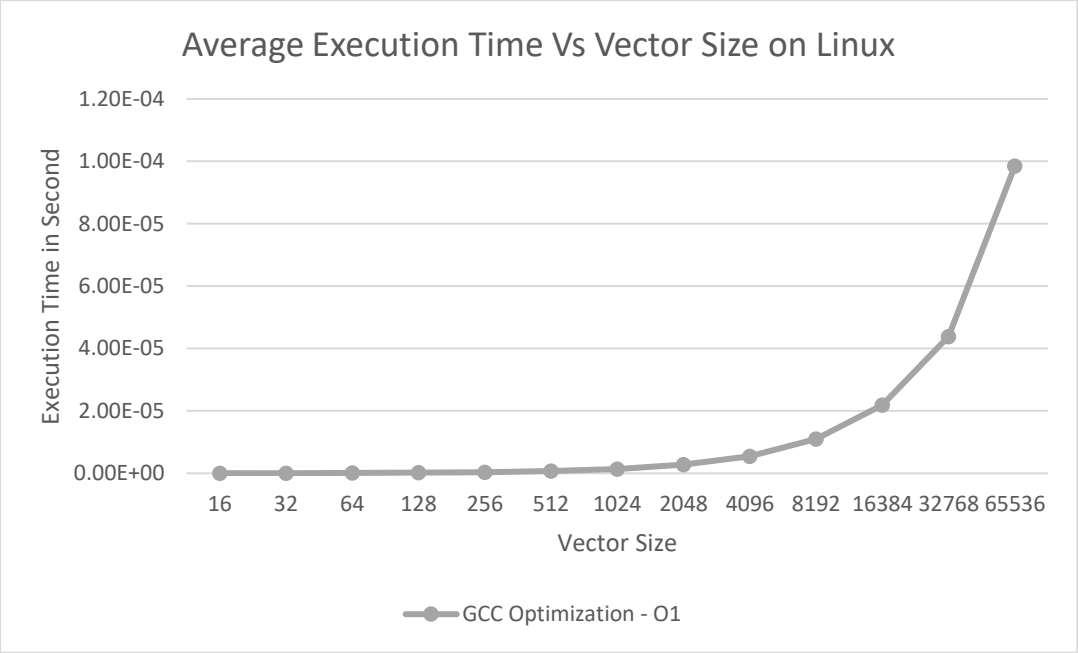
Graph

On the Table and graph below, we can see the execution time in Linux for O1 optimization after we run the code.

Table 10 - Execution time for Compiler Generated Optimization with O1

Vector Size	Execution time in second for GCC Optimization with O1
16	5.26E-08
32	6.44E-08
64	1.08E-07
128	1.93E-07
256	3.66E-07
512	7.23E-07
1024	1.39E-06
2048	2.76E-06
4096	5.50E-06
8192	1.10E-05
16384	2.19E-05
32768	4.38E-05

65536	9.85E-05



Graph 8 - Execution time for Compiler Generated Optimization with O1

Complete Assembly Code for O1

Below we can see the O1 optimization complete assembly Code in Linux.

```
1         .file   "Peiravani_Paniz_dotProduct.cpp"
2         .text
3         .globl  _Z10dotProductRKSt6vectorIfSaIfEES3_i
4         .type   _Z10dotProductRKSt6vectorIfSaIfEES3_i, @function
5 _Z10dotProductRKSt6vectorIfSaIfEES3_i:
6 .LFB865:
7         .cfi_startproc
8         endbr64
9         testl   %edx, %edx
10        jle     .L8
11        movq    (%rdi), %rdi
12        movq    (%rsi), %rcx
13        leal    -1(%rdx), %eax
14        cmpl    $2, %eax
15        jbe     .L9
16        movl    %edx, %esi
17        shrl    $2, %esi
18        movl    %esi, %esi
19        salq    $4, %rsi
20        movl    $0, %eax
21        pxor    %xmm0, %xmm0
22 .L4:
23        movups  (%rdi,%rax), %xmm1
24        movups  (%rcx,%rax), %xmm3
25        mulps   %xmm3, %xmm1
26        addss   %xmm1, %xmm0
27        movaps  %xmm1, %xmm2
28        shufps  $85, %xmm1, %xmm2
29        addss   %xmm2, %xmm0
30        movaps  %xmm1, %xmm2
31        unpckhps        %xmm1, %xmm2
32        addss   %xmm2, %xmm0
```

Figure 74 - Optimized O1 on Linux

```
32          addss   %xmm2, %xmm0
33          shufps  $255, %xmm1, %xmm1
34          addss   %xmm1, %xmm0
35          addq    $16, %rax
36          cmpq    %rsi, %rax
37          jne     .L4
38          movl    %edx, %esi
39          andl    $-4, %esi
40          movl    %esi, %eax
41          cmpl    %esi, %edx
42          je      .L12
43 .L3:
44          cltq
45 .L7:
46          movss   (%rdi,%rax,4), %xmm1
47          mulss   (%rcx,%rax,4), %xmm1
48          addss   %xmm1, %xmm0
49          addq    $1, %rax
50          cmpl    %eax, %edx
51          jg      .L7
52          ret
53 .L12:
54          ret
55 .L9:
56          movl    $0, %eax
57          pxor    %xmm0, %xmm0
58          jmp     .L3
59 .L8:
60          pxor    %xmm0, %xmm0
61          ret
62          .cfi_endproc
63 .LFE865:
```

Figure 75 - Optimized O1 on Linux

```
63 .LFE865:
64          .size   _Z10dotProductRKSt6vectorIfSaIfEES3_i, .-_Z10dotProductRKSt6vectorIfSaIfEES3_i
65          .ident  "GCC: (Ubuntu 11.3.0-1ubuntu1~22.04) 11.3.0"
66          .section        .note.GNU-stack,"",@progbits
67          .section        .note.gnu.property,"a"
68          .align 8
69          .long   1f - 0f
70          .long   4f - 1f
71          .long   5
72 0:
73          .string "GNU"
74 1:
75          .align 8
76          .long   0xc0000002
77          .long   3f - 2f
78 2:
79          .long   0x3
80 3:
81          .align 8
82 4:
```

Figure 76 - Optimized O1 on Linux

O2 - Optimization

Now we are going to find the execution time using O2 optimization flags which level 2 and is more recommended. O2 more focus to optimize for speed.

```
g++ -O2 -ftree-loop-distribute-patterns -ftree-vectorize -mavx2
Peiravani_Paniz_dotProduct.cpp -o Peiravani_Paniz_dotProduct_OptO1 -S
```

```
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ g++ -O2 -ftree-loop-distribute-patterns
-ftree-vectorize -mavx Peiravani_Paniz_dotProduct.cpp -o Peiravani_Paniz_dotProduct_OptO2 -S
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$
```

Figure 77 - get Assembly O2 optimize on Linux

After we run the O2 optimized code, we can see the execution time is less than from non-Optimized.

```
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ g++ -O2 -ftree-loop-distribute-patterns
-ftree-vectorize -mavx Peiravani_Paniz_main.cpp Peiravani_Paniz_dotProduct.cpp -o Peiravani_Pa
niz_dotProduct_OptO2
paniz@paniz-VirtualBox:~/Desktop/1. Final - Part two$ ./Peiravani_Paniz_dotProduct_OptO2
```

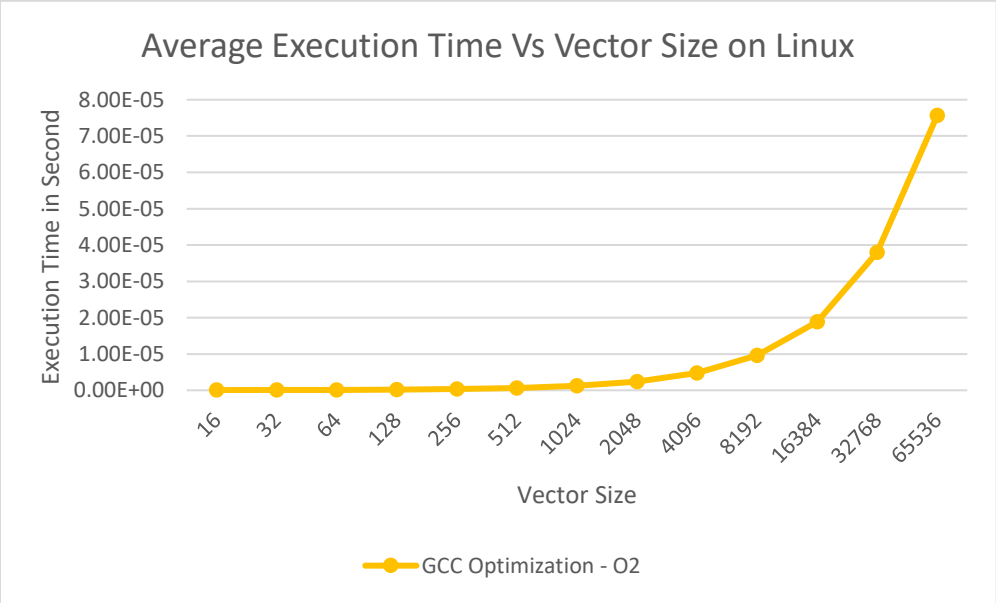
Figure 78 - run the C++ code with O2 Optimization

Graph

On the Table and graph below, we can see the execution time in Linux for O2 optimization after we run the code.

Table 11 - Execution time for Compiler Generated Optimization with O2

Vector Size	Ecevution time in second for GCC Optimization with O2
16	5.44E-08
32	6.27E-08
64	9.91E-08
128	1.74E-07
256	3.21E-07
512	6.15E-07
1024	1.20E-06
2048	2.37E-06
4096	4.72E-06
8192	9.57E-06
16384	1.88E-05
32768	3.79E-05
65536	7.57E-05



Graph 9 - Execution time for Compiler Generated Optimization with O2

Complete Assembly Code for O2

Below we can see the O2 optimization complete assembly Code in Linux.

```
1         .file   "Peiravani_Paniz_dotProduct.cpp"
2         .text
3         .globl  _Z10dotProductRKSt6vectorIfSaIfEES3_i
4         .type   _Z10dotProductRKSt6vectorIfSaIfEES3_i, @function
5 _Z10dotProductRKSt6vectorIfSaIfEES3_i:
6 .LFB865:
7         .cfi_startproc
8         endbr64
9         pushq   %rbp
10        .cfi_def_cfa_offset 16
11        .cfi_offset 6, -16
12        movq    %rsp, %rbp
13        .cfi_def_cfa_register 6
14        subq    $48, %rsp
15        movq    %rdi, -24(%rbp)
16        movq    %rsi, -32(%rbp)
17        movl    %edx, -36(%rbp)
18        pxor    %xmm0, %xmm0
19        movss   %xmm0, -8(%rbp)
20        movl    $0, -4(%rbp)
21        jmp     .L2
22 .L3:
23        movl    -4(%rbp), %eax
24        movslq  %eax, %rdx
25        movq    -24(%rbp), %rax
26        movq    %rdx, %rsi
27        movq    %rax, %rdi
28        call    _ZNKSt6vectorIfSaIfEEixEm
29        movss   (%rax), %xmm2
30        movss   %xmm2, -40(%rbp)
31        movl    -4(%rbp), %eax
32        movslq  %eax, %rdx
33        movq    -32(%rbp), %rax
```

Figure 79 - O2 optimization on Linux

```
33        movq    -32(%rbp), %rax
34        movq    %rdx, %rsi
35        movq    %rax, %rdi
36        call    _ZNKSt6vectorIfSaIfEEixEm
37        movss   (%rax), %xmm0
38        mulss   -40(%rbp), %xmm0
39        movss   -8(%rbp), %xmm1
40        addss   %xmm1, %xmm0
41        movss   %xmm0, -8(%rbp)
42        addl    $1, -4(%rbp)
43 .L2:
44        movl    -4(%rbp), %eax
45        cmpl    -36(%rbp), %eax
46        jl      .L3
47        movss   -8(%rbp), %xmm0
48        leave
49        .cfi_def_cfa 7, 8
50        ret
51        .cfi_endproc
52 .LFE865:
53        .size   _Z10dotProductRKSt6vectorIfSaIfEES3_i, .-_Z10dotProductRKSt6vectorIfSaIfEES3_i
54        .section        .text._ZNKSt6vectorIfSaIfEEixEm,"axG",@progbits,_ZNKSt6vectorIfSaIfEEixEm,comdat
55        .align 2
56        .weak   _ZNKSt6vectorIfSaIfEEixEm
57        .type   _ZNKSt6vectorIfSaIfEEixEm, @function
58 _ZNKSt6vectorIfSaIfEEixEm:
59 .LFB868:
60        .cfi_startproc
61        endbr64
62        pushq   %rbp
63        .cfi_def_cfa_offset 16
64        .cfi_offset 6, -16
65        movq    %rsp, %rbp
```

Figure 80 - O2 optimization on Linux

```
65          movq    %rsp, %rbp
66          .cfi_def_cfa_register 6
67          movq    %rdi, -8(%rbp)
68          movq    %rsi, -16(%rbp)
69          movq    -8(%rbp), %rax
70          movq    (%rax), %rdx
71          movq    -16(%rbp), %rax
72          salq    $2, %rax
73          addq    %rdx, %rax
74          popq    %rbp
75          .cfi_def_cfa 7, 8
76          ret
77          .cfi_endproc
78 .LFE868:
79          .size   _ZNKSt6vectorIfSaIfEEixEm, .-_ZNKSt6vectorIfSaIfEEixEm
80          .ident  "GCC: (Ubuntu 11.3.0-1ubuntu1~22.04) 11.3.0"
81          .section        .note.GNU-stack,"",@progbits
82          .section        .note.gnu.property,"a"
83          .align 8
84          .long   1f - 0f
85          .long   4f - 1f
86          .long   5
87 0:
88          .string "GNU"
89 1:
90          .align 8
91          .long   0xc0000002
92          .long   3f - 2f
93 2:
94          .long   0x3
95 3:
96          .align 8
97 4:
```

Figure 81 - O2 optimization on Linux

Manually Optimization

Now we are manually optimizing the code. The red lines show the code that I can remove and the green lines the code that I optimized. One way to optimize is to reduce the use of `mov` instructions by reusing registers or rearranging instructions and changing bytes storage for memory usage and speed.

```
        .file  "Peiravani_Paniz_dotProduct.cpp"
        .text
        .p2align
        .globl _Z10dotProductRKSt6vectorIfSaIfEES3_i
        .type  _Z10dotProductRKSt6vectorIfSaIfEES3_i, @function
_Z10dotProductRKSt6vectorIfSaIfEES3_i:
.LFB865:
        .cfi_startproc
        endbr64
        testl  %edx, %edx
        jle    .L10
        jle    .L4
        leal   -1(%rdx), %eax
        movq   (%rdi), %rd
        movq   (%rsi), %rcx
        cmpl   $6, %eax
        jbe    .L11
        movl   %edx, %esi
        movslq %edx, %rdx
        xorl   %eax, %eax
        vxorps %xmm0, %xmm0, %xmm0
        vxorps %xmm1, %xmm1, %xmm1
        shrl   $3, %esi
        salq   $5, %rsi
        .p2align 4,,10
        .p2align 3
```

```
.L4:
        vmovups      (%rdi,%rax), %ymm4
        vmulps (%rcx,%rax), %ymm4, %ymm1
        addq   $32, %rax
        vaddss %xmm1, %xmm0, %xmm0
        vshufps      $85, %xmm1, %xmm1, %xmm3
        vshufps      $255, %xmm1, %xmm1, %xmm2
        vaddss %xmm3, %xmm0, %xmm0
        vunpckhps    %xmm1, %xmm1, %xmm3
        vextractf128 $0x1, %ymm1, %xmm1
        vaddss %xmm3, %xmm0, %xmm0
        vaddss %xmm2, %xmm0, %xmm0
        vshufps      $85, %xmm1, %xmm1, %xmm2
        vaddss %xmm1, %xmm0, %xmm0
        vaddss %xmm2, %xmm0, %xmm0
        vunpckhps    %xmm1, %xmm1, %xmm2
        vshufps      $255, %xmm1, %xmm1, %xmm1
        vaddss %xmm2, %xmm0, %xmm0
        vaddss %xmm1, %xmm0, %xmm0
        cmpq   %rsi, %rax
        jne    .L4
        movl   %edx, %esi
        andl   $-8, %esi
        movl   %esi, %eax
        cmpl   %esi, %edx
        je     .L16
        vzeroupper
.L3:
        vmovss (%rdi,%rax,4), %xmm0
        movl   %edx, %r8d
        subl   %esi, %r8d
        leal   -1(%r8), %r9d
        cmpl   $2, %r9d
        jbe    .L7
        vmovups      (%rdi,%rsi,4), %xmm5
        vmulps (%rcx,%rsi,4), %xmm5, %xmm1
        movl   %r8d, %esi
        andl   $-4, %esi
        addl   %esi, %eax
        vaddss %xmm1, %xmm0, %xmm0
        vshufps      $85, %xmm1, %xmm1, %xmm2
        vaddss %xmm2, %xmm0, %xmm0
        vunpckhps    %xmm1, %xmm1, %xmm2
        vshufps      $255, %xmm1, %xmm1, %xmm1
        vaddss %xmm2, %xmm0, %xmm0
        vaddss %xmm1, %xmm0, %xmm0
        cmpl   %esi, %r8d
        je     .L1
.L7:
        cltq
        .p2align 4,,10
        .p2align 3
.L9:
        vmovss (%rdi,%rax,4), %xmm1
        vmulss (%rcx,%rax,4), %xmm1, %xmm1
```

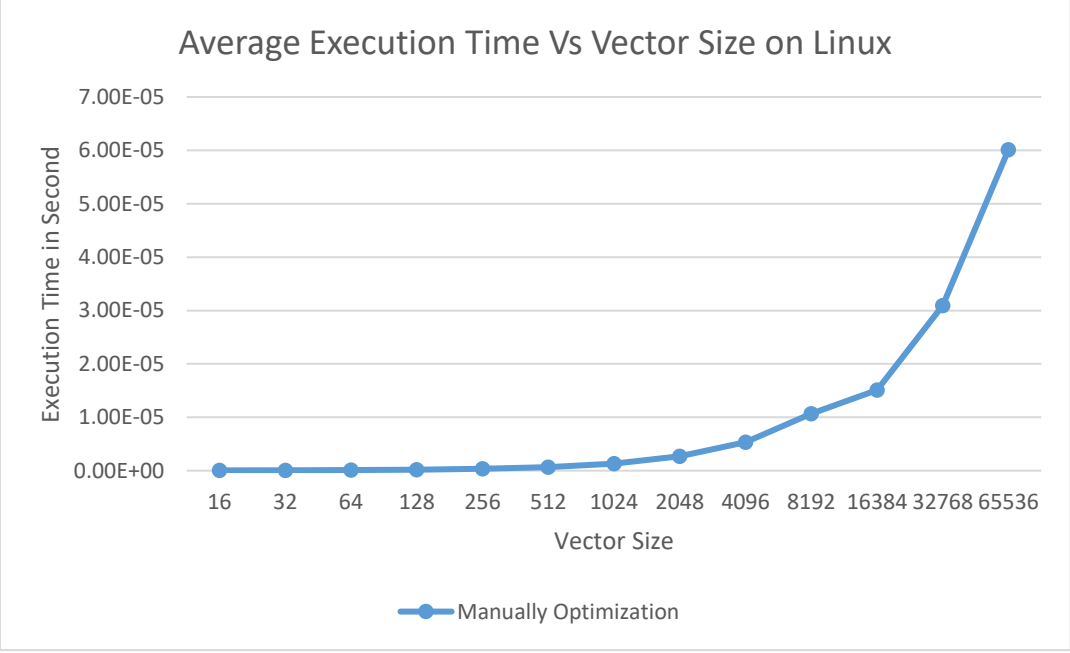
```
        vmulss (%rcx,%rax,4), %xmm0, %xmm0
        addq   $1, %rax
        vaddss %xmm1, %xmm0, %xmm0
        vaddss %xmm0, %xmm1, %xmm1
        cmpl   %eax, %edx
        cmpq   %rax, %rdx
        jg     .L9
        jg     .L3
        vmovaps         %xmm1, %xmm0
        ret
        .p2align 4,,10
        .p2align 3
.L10:
        vxorps %xmm0, %xmm0, %xmm0
.L1:
        ret
        .p2align 4,,10
        .p2align 3
.L16:
        vzeroupper
        ret
.L11:
        xorl   %esi, %esi
        xorl   %eax, %eax
        vxorps %xmm0, %xmm0, %xmm0
        jmp    .L3
        .cfi_endproc
.LFE865:
        .size  _Z10dotProductRKSt6vectorIfSaIfEES3_i, .-
_Z10dotProductRKSt6vectorIfSaIfEES3_i
        .ident "GCC: (Ubuntu 11.3.0-1ubuntu1~22.04) 11.3.0"
        .section     .note.GNU-stack,"",@progbits
        .section     .note.gnu.property,"a"
        .align 8
        .long  1f - 0f
        .long  4f - 11
        .long  5
0:
        .string      "GNU"
1:
        .align 8
        .long  0xc0000002
        .long  3f - 2f
2:
        .long  0x3
3:
        .align 8
.L4:
         vxorps         %xmm1, %xmm1, %xmm1
         vmovaps         %xmm1, %xmm
        ret
.cfi_endproc
```

Graph

And after we run the code, we can see that the execution time is less than before. Below table shows the execution time of our manually optimization code.

Table 12 - Execution Time for Manually Optimization on Linux

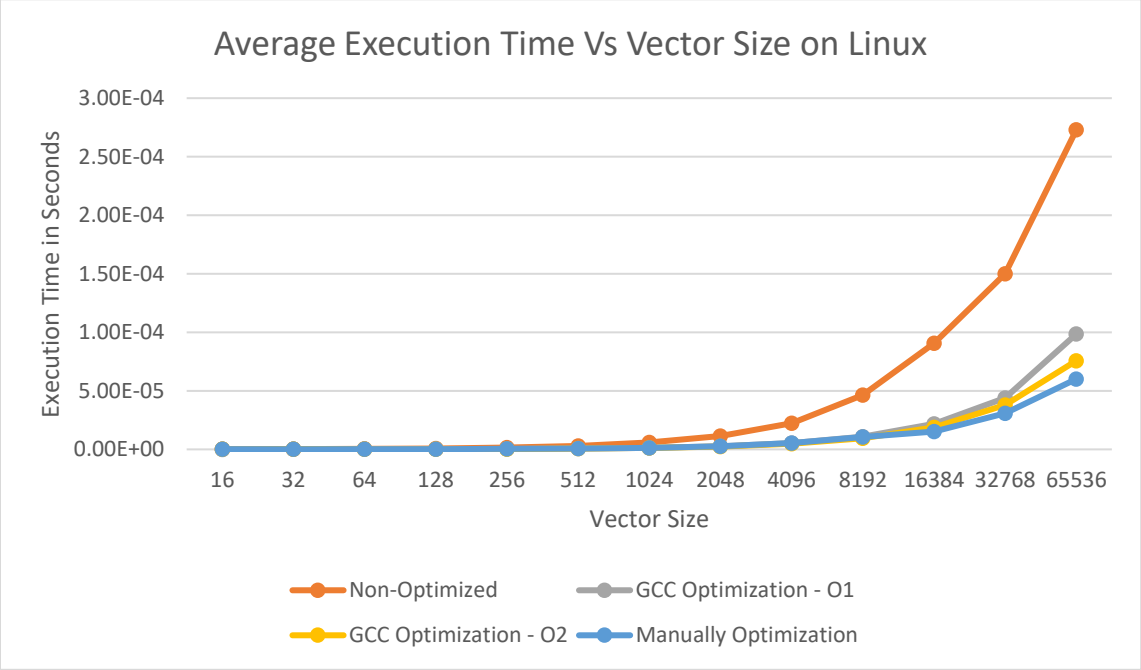
Vector Size	Execution time in second for Manually Optimized on Linux
16	7.06E-08
32	7.04E-08
64	1.08E-07
128	1.86E-07
256	3.47E-07
512	6.84E-07
1024	1.35E-06
2048	2.70E-06
4096	5.35E-06
8192	1.07E-05
16384	1.51E-05
32768	3.09E-05
65536	6.01E-05



Graph 10 - Execution Time for Manually Optimization on Linux

Graph

Now that we have our execution time for non-optimized, O1 compiler optimization, O2 compiler optimization, and manually optimization we can put the execution time on graph to compare the executions times on Linux, Ubuntu.



Graph 11 - Task 3 for Linux

Task 4 – DPPS

Windows – Intel x64

Now we are going to use Determinantal point processes, DPPS. DPPS vector instruction will optimize the code further. In other words, DPPS has better performance, and it is faster. We will use DPPS in our *dotProduct.cpp* since in that file out dot Products computers. Below is our DPPS code for our dotProcut. The only update that we need to out main.cpp is that to change the format that it calls dotProduct to be same as the one in out dotProduct.cpp.

```cpp
#include <immintrin.h>

// Calculate the dot product of two float arrays using the DPPS
float dotProduct_DPPS(float* a, float* b, int size)
{
    // Declare 256-bit wide vector registers
    // initialize ymm2 to zero
    __m256 ymm0, ymm1, ymm2 = _mm256_setzero_ps();
    const int resultV = 0xF1;   // resultV for DPPS instruction
    float product = 0.0;

    // Loop through the arrays in parallel
    // processing 8 elements at a time
#pragma loop(hint_parallel(8))
    for (int i = 0; i < size / 8; i++) {
        // Load 8 float values from array 'a' into ymm0
        ymm0 = _mm256_load_ps(a + 1 * 8);
        // Load 8 float values from array 'b' into ymm1
        ymm1 = _mm256_load_ps(b + 1 * 8);
        // Perform dot product using DPPS instruction and store the result in ymm2
        ymm2 = _mm256_dp_ps(ymm0, ymm1, resultV);

        // Convert the address of the ymm0 vector register to a float pointer
        float* temp = (float*)&ymm0;
        // Add the first and fifth elements in ymm0 to the product
        product += (temp[0] + temp[4]);
    }

    return product;
}
```

Graph 12 - DPPS

Run the Code

After we run the code, we can see that the execution time is less than previous steps.

```
Vector size: 16
Average time: 4e-08
---------------------------------------
Vector size: 32
Average time: 8e-08
---------------------------------------
Vector size: 64
Average time: 1.2e-07
---------------------------------------
Vector size: 128
Average time: 1.3e-07
---------------------------------------
Vector size: 256
Average time: 1.9e-07
---------------------------------------
Vector size: 512
Average time: 2.3e-07
---------------------------------------
Vector size: 1024
Average time: 2.6e-07
---------------------------------------
Vector size: 2048
Average time: 2.8e-07
---------------------------------------
Vector size: 4096
Average time: 3.4e-07
---------------------------------------
Vector size: 8192
Average time: 4.1e-07
---------------------------------------
Vector size: 16384
Average time: 4.6e-07
---------------------------------------
Vector size: 32768
Average time: 5e-07
---------------------------------------
```

Figure 82 - DPPS Result

```
------------------------------------
Vector size: 32768
Average time: 5e-07
------------------------------------
Vector size: 65536
Average time: 5.4e-07
------------------------------------
```

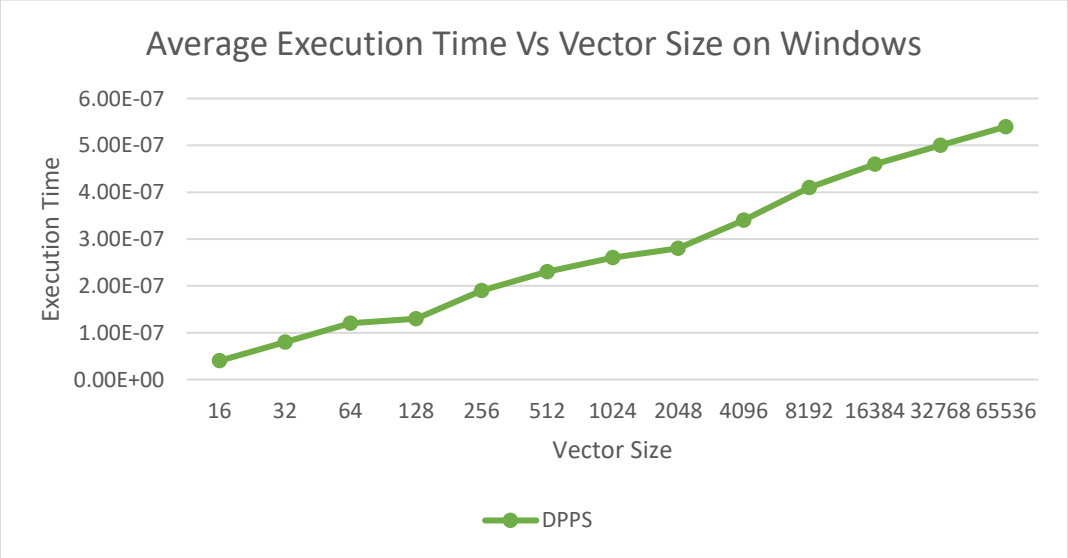
Figure 83 - DPPS Result

Graph

Now that we have execution time, we will graph Average Execution time Vs vector size for unoptimized code. We ran the code 10 times for each vector size to be able to find the average execution time that is more accurate.

Table 13 - DPPS for Windows

Vector Size	Execution time in seconds for DPPS on Windows
16	4.00E-08
32	8.00E-08
64	1.20E-07
128	1.30E-07
256	1.90E-07
512	2.30E-07
1024	2.60E-07
2048	2.80E-07
4096	3.40E-07
8192	4.10E-07
16384	4.60E-07
32768	5.00E-07
65536	5.40E-07



Graph 13 - DPPS for Windows

Linux – Ubuntu

Now we are going to use Determinantal point processes, DPPS. DPPS vector instruction will optimize the code further. In other words, DPPS has better performance, and it is faster. We will use DPPS in our *dotProduct.cpp* since in that file out dot Products computers. Below is our DPPS code for our dotProcut. The only update that we need to out main.cpp is that change the format that it calls dotProduct to be same as the one in out dotProduct.cpp.

```cpp
#include <immintrin.h>
#include <stdio.h>

// Calculate the dot product of two float arrays using the DPPS instruction
float dotProduct_DPPS(float* a, float* b, int size)
{
// Declare 256-bit wide vector registers and initialize ymm2 to zero
    __m256 ymm0, ymm1, ymm2 = _mm256_setzero_ps();
    const int resultV = 0xF1;   // resultV for DPPS instruction
    float product = 0.0;

// Loop through the arrays in parallel, processing 8 elements at a time
#pragma loop(hint_parallel(8))
    for (int i = 0; i < size / 8; i++) {
        // Load 8 float values from array 'a' into ymm0
        ymm0 = _mm256_loadu_ps(a + i * 8);
        // Load 8 float values from array 'b' into ymm1
        ymm1 = _mm256_loadu_ps(b + i * 8);
        // Perform dot product using DPPS instruction and store the result in ymm2
        ymm2 = _mm256_dp_ps(ymm0, ymm1, resultV);

        // Convert the address of the ymm2 vector register to a float pointer
        float* temp = (float*)&ymm2;
        // Add the first and fifth elements in ymm2 to the product
        product += (temp[0] + temp[4]);
    }

    return product;
}
```

Figure 84 – DPPs

Run the Code

In order for our code to run, we need to use AVX instruction which we know our CPU supports based on task 1.

```
paniz@paniz-VirtualBox:~/Desktop/DPPS$ g++ -mavx main.cpp dpps.cpp
-o DPPs
paniz@paniz-VirtualBox:~/Desktop/DPPS$ ./DPPs
```

Figure 85 - Run DPPs on Linux

```
ector size: 16
verage time: 5.87e-08
---------------------------------------
ector size: 32
verage time: 5.71e-08
---------------------------------------
ector size: 64
verage time: 7.02e-08
---------------------------------------
ector size: 128
verage time: 1.008e-07
---------------------------------------
ector size: 256
verage time: 1.657e-07
---------------------------------------
ector size: 512
verage time: 3.086e-07
---------------------------------------
ector size: 1024
verage time: 5.668e-07
---------------------------------------
ector size: 2048
verage time: 1.1153e-06
---------------------------------------
ector size: 4096
verage time: 2.1556e-06
---------------------------------------
```

Figure 86 - DPPs result

```
Vector size: 8192
Average time: 4.4401e-06
---------------------------------------
Vector size: 16384
Average time: 8.8926e-06
---------------------------------------
Vector size: 32768
Average time: 2.58451e-05
---------------------------------------
Vector size: 65536
Average time: 4.08041e-05
---------------------------------------
```

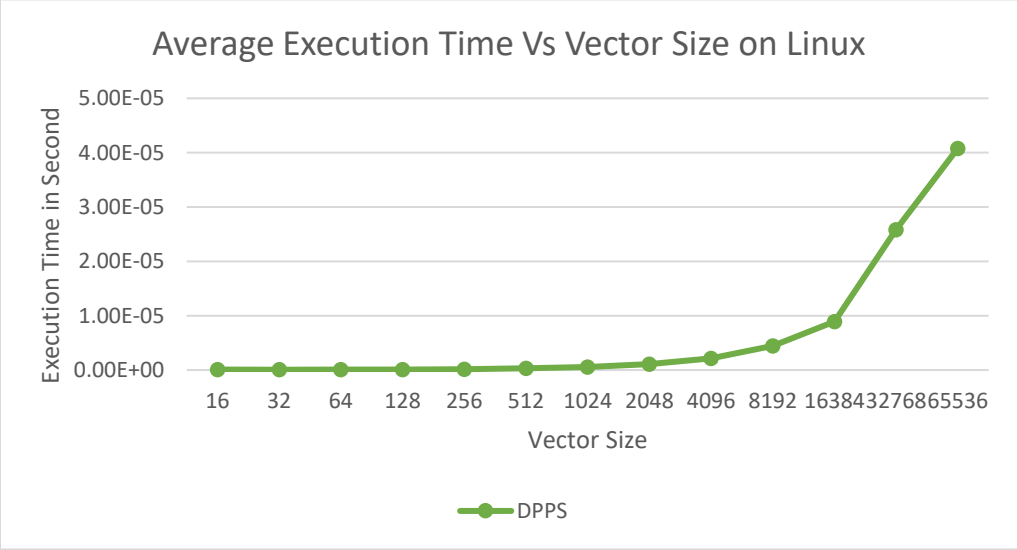
Figure 87 - DPPs result

Graph

Now that we have execution time, we will graph Average Execution time Vs vector size for unoptimized code. We ran the code 10 times for each vector size to be able to find the average execution time that is more accurate.

Table 14 - DPPs on Linux

Vector Size	Execution time in seconds for DPPs on Linux
16	5.87E-08
32	5.71E-08
64	7.02E-08
128	1.01E-07
256	1.66E-07
512	3.09E-07
1024	5.67E-07
2048	1.12E-06
4096	2.16E-06
8192	4.44E-06
16384	8.89E-06
32768	2.58E-05
65536	4.08E-05



Graph 14 - DPPs Graph

Task 5 – All Plots in on Graph

Windows – Intel x64

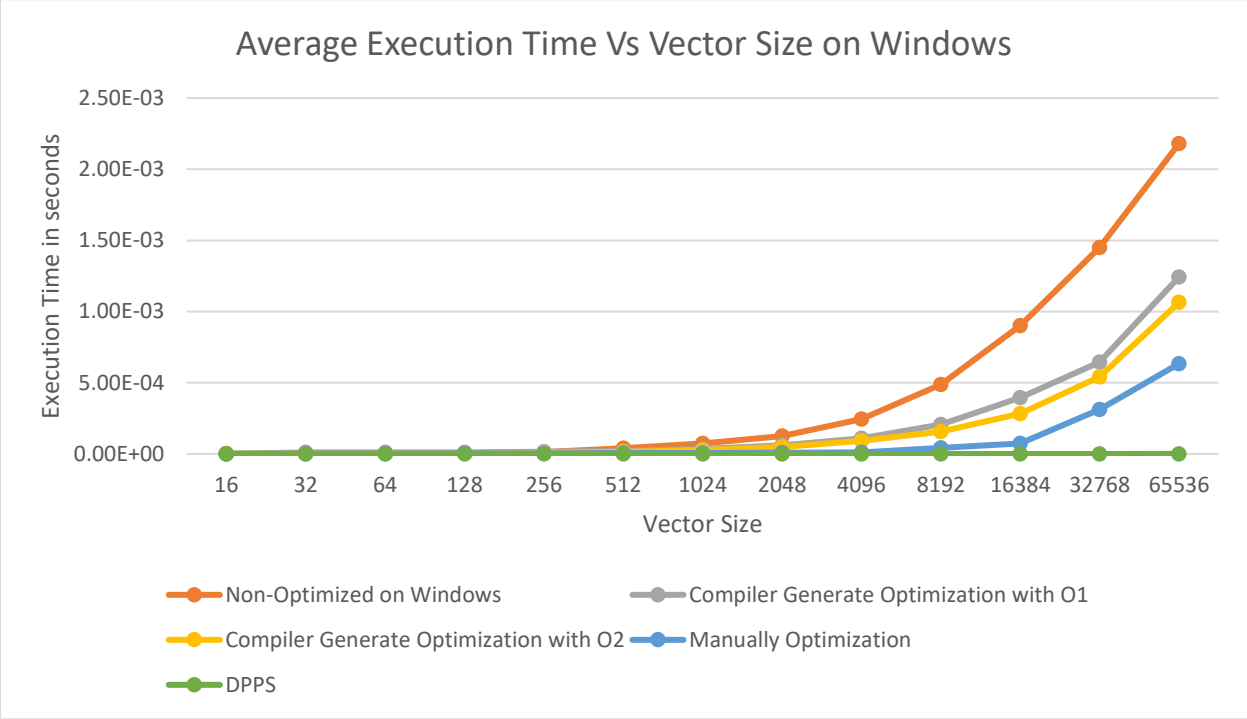
Now that we have finished tasks 1 to 4, we are going to compare all of the result in one graph. Below you can see the table that includes all the execution times that we found out for each task in windows.

Table 15 – Windows Intel x64

Vector Size	Non-Optimized	Compiler Optimization - O1	Compiler Optimization - O2	Manually Optimization	DPPS
16	8.20E-07	6.90E-07	6.60E-07	4.70E-07	4.00E-08
32	2.04E-06	9.97E-06	1.55E-06	1.97E-06	8.00E-08
64	3.84E-06	1.08E-05	2.88E-06	2.46E-06	1.20E-07
128	6.71E-06	1.17E-05	4.64E-06	4.19E-06	1.30E-07
256	1.28E-05	1.50E-05	8.25E-06	4.90E-06	1.90E-07
512	4.05E-05	2.00E-05	1.44E-05	6.05E-06	2.30E-07
1024	7.33E-05	3.64E-05	2.68E-05	7.15E-06	2.60E-07
2048	1.25E-04	6.06E-05	4.82E-05	9.10E-06	2.80E-07
4096	2.44E-04	1.10E-04	9.27E-05	1.16E-05	3.40E-07
8192	4.87E-04	2.07E-04	1.57E-04	4.23E-05	4.10E-07
16384	9.00E-04	3.95E-04	2.82E-04	7.45E-05	4.60E-07
32768	1.45E-03	6.46E-04	5.42E-04	3.12E-04	5.00E-07
65536	2.18E-03	1.24E-03	1.06E-03	6.34E-04	5.40E-07

If you look at the graph, we can see the the order of execution time from fast to slow is from Non-Optimization, Compiler optimization - O1, Compiler Optimization - O2, manually Optimization, and DPPS

Table 16 – Windows Intel x64



Linux – Ubuntu

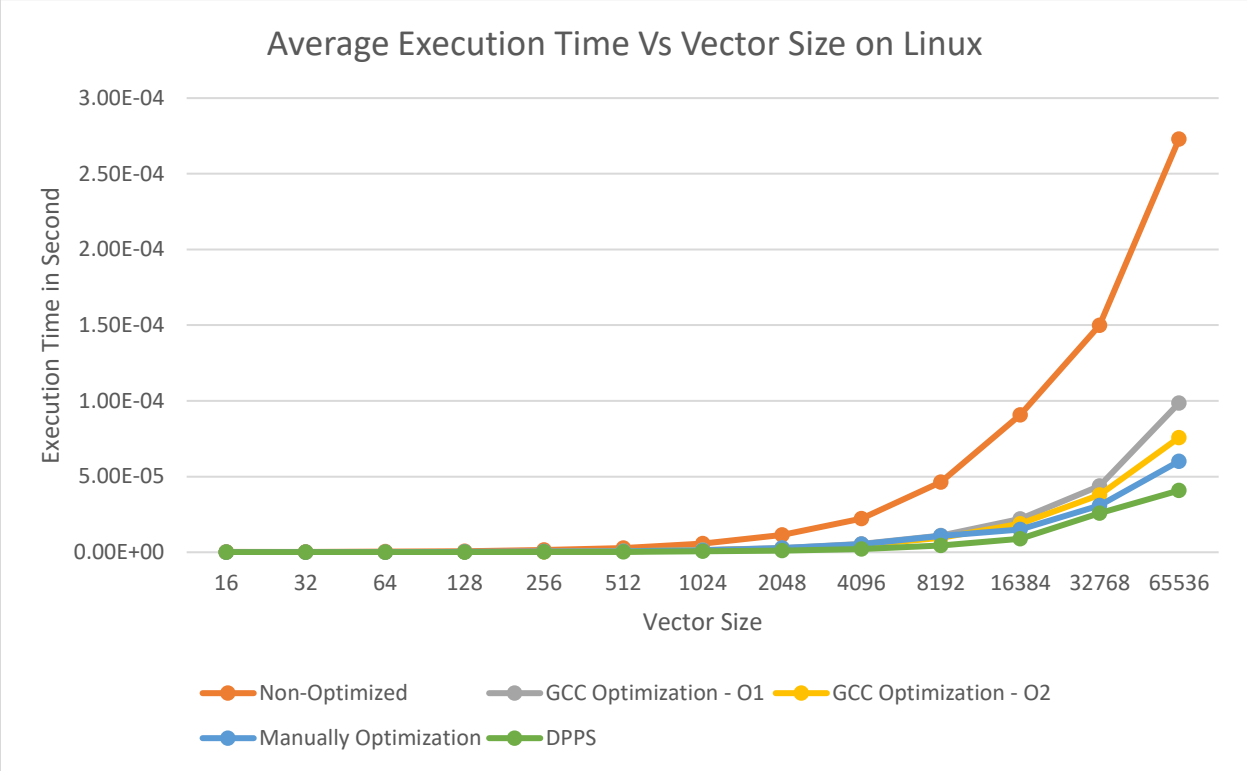
Now that we have finished tasks 1 to 4, we are going to compare all of the result in one graph. Below you can see the table that includes all the execution times that we found out for each task in Linux.

Table 17 – Linux, Ubuntu

Vector Size	Non-Optimized	GCC Optimization - O1	GCC Optimization - O2	Manually Optimization	DPPS
16	2.28E-07	5.26E-08	5.44E-08	7.06E-08	5.87E-08
32	2.17E-07	6.44E-08	6.27E-08	7.04E-08	5.71E-08
64	3.97E-07	1.08E-07	9.91E-08	1.08E-07	7.02E-08
128	7.36E-07	1.93E-07	1.74E-07	1.86E-07	1.01E-07
256	1.43E-06	3.66E-07	3.21E-07	3.47E-07	1.66E-07
512	2.82E-06	7.23E-07	6.15E-07	6.84E-07	3.09E-07
1024	5.83E-06	1.39E-06	1.20E-06	1.35E-06	5.67E-07
2048	1.14E-05	2.76E-06	2.37E-06	2.70E-06	1.12E-06
4096	2.23E-05	5.50E-06	4.72E-06	5.35E-06	2.16E-06
8192	4.63E-05	1.10E-05	9.57E-06	1.07E-05	4.44E-06
16384	9.07E-05	2.19E-05	1.88E-05	1.51E-05	8.89E-06
32768	1.50E-04	4.38E-05	3.79E-05	3.09E-05	2.58E-05
65536	2.73E-04	9.85E-05	7.57E-05	6.01E-05	4.08E-05

If you look at the graph, we can see the the order of execution time from fast to slow is from Non-Optimization, Compiler optimization - O1, Compiler Optimization - O2, manually Optimization, and DPPS

Table 18 - Linux, Ubuntu



Conclusion

In conclusion, this final take-home assignment focused on optimizing compiler-generated code for computing dot products using vector instructions. This take-home test needed to be implemented on two different operating system. I used Windows intel x64 and Linux, Ubuntu. First, I determine my CPU ID to see which vector instructions I can use that my CPU will support. Next, I generated a C++ code which has two separate files. One for main function and one for calculating the dot product. First, I disable automatic parallelization and automatic vectorization to observe the output. After that I enable them to see the output for optimizations. For optimization, I used O1, O2 flags and then I manually optimized the assembly code myself as well. I also used DPPs for more optimizations. For each task, I found the execution time. I ran the code times and saved the average execution times so the result be more accurate. Lastly, I compare all the graphs for each task to observe how does optimization works. Overall, From the graph, I observed that the order of execution time from fastest to slowest was Non-Optimization, Compiler optimization - O1, Compiler Optimization - O2, manually Optimization, and DPPS.